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Thermo-Systems, Incorporated

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STATE OF THE ART: 1971 INSTRUMENTATION FOR MEASUREMENT OF PARTICULATE EMISSIONS FROM COMBUSTION SOURCES VOLUME III: PARTICLE SIZE

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FOREWORD

The compilation of the information contained in this publication was performed pursuant to Contract CPA 70-23 for the Environmental Protection Agency. The work was sponsored by the National Environmental Research Center at Research Triangle Park for the purpose of conception and evaluation of instrument systems for particle size distribution applicable to the measurement of emissions from stationary sources.

This report was prepared during the period from January to August, 1971, and is the third of a four volume series. These volumes contain the following:

Volume I of this report is written for the engineer or planner who needs to know a few basic facts about a particulate mass measurement technique and wishes to minimize the time required to obtain this information. Volume I is intended for use as a quick reference guide.

Volume II of this report is designed as a detailed in-depth report on operating principles, techniques, historical data, and discussion of the more viable techniques for particulate mass monitoring. Volume II is designed for the plant engineer, abatement and control officials, and others who may not be familiar with the detailed technology of these areas. Included are sections on power plant emissions properties and extraction sampling probes.

Volume III of this report is a comprehensive survey of particle sizing techniques which may be used by the plant engineer, abatement and control officials, and others as a quick reference guide or as a source of more detailed information, including references to original work.

Volume IV of this report describes an experimental evaluation of the beta radiation attenuation technique for mass concentration measurements on a coal-fired power generating plant. Problem areas requiring further developments are identified for personnel concerned with improving the techniques.

These reports have been issued as they were completed to make them available to the public on a timely basis. Volume I and II were issued in September 1971. Volume IV will be issued late this Fall.

ABSTRACT AND CONCLUSION

Volume III (this volume) discusses candidate techniques for automatic or semi-automatic measurement of particle size distribution in combustion source effluents. Automatic or semi-automatic particle size measuring instruments do not yet exist for this application. This report considers the application to effluent streams of particle size measuring instruments used in other fields. The discussions emphasize the particulate concentration parameter (mass, number, surface area, etc.) which each technique senses as well as the method of classifying particles into size ranges (aerodynamically, electrostatically, optically, etc.) Included are descriptions of the basic operation of each technique, discussions of limitations of each technique, suggestions of possible major problems in applying each technique to effluent streams and an overall evaluation of each technique relative to others.

The most promising approach for detailed size analysis on a routine basis at this time is an aerodynamic particle size classifier combined with either beta radiation attenuation, piezoelectric microbalance, or photometric concentration sensors. The impactor classifies particles aerodynamically, the most useful method for most air pollution applications. The beta and piezoelectric sensors (see Volume I and II of this report for discussion of sensors) can detect the mass concentration, while a correctly-designed photometric sensor detects a parameter (related to surface area) which could be used as an indicator of the effect of the emissions on visibility. Although the more promising aerodynamic techniques can classify particles in an approximate range from 0.2 to 30 microns, the particles above and below these limits could be lumped into separate size categories, permitting a gravimetric size measurement covering nearly the entire range of particles found in effluent streams (from about 0.001 to above 100 microns).

Several techniques appear applicable to special sizing problems in effluent streams. Cyclone classifiers can be used to separate the "respirable fraction" of particles. Electrostatic and diffusion classifiers can possibly be used to measure detailed size distributions in the range from 0.001 to 0.6 microns. Modified optical particle counters may be useful for some research applications. Holography offers the ability to photograph (in 3-dimension) the effluent particles in the stream without disturbing them in any way, but appears limited for most sizing applications by its lower particle size resolution when operated across stack distances, by its cost, and by its complexity.

Another concept looks promising for use as a continuous, routine monitoring technique for effluent streams. The technique uses the size limitations of at least three particle concentration monitors to measure particle concentration in three or more size ranges. Three candidate concentration monitors measure: (1) the mass concentration (sensitive primarily to 1 - 100 micron particles), (2) the opacity of the effluent stream (sensitive primarily to 0.1 - 10 micron particles), and (3) the number concentration (sensitive primarily to 0.001 - 1.0 micron particles).

Respirable mass concentration is another promising candidate. Instruments which measure most of these parameters have already been used in effluents so only a moderate amount of hardware development appears needed. Simple analysis of such measurements made simultaneously may provide sufficient particle size and concentration information for most routine monitoring applications.

Although not covered in this report, considerable research and development must be done to develop sampling systems which can deliver truly representative particle samples to the sizing instruments. No practical candidate for automated sizing exists which has sufficient resolution to cover the most important effluent size range and which does not require extraction of a sample from the effluent stream.

INSTRUMENTATION FOR MEASUREMENT OF PARTICULATE EMISSIONS FROM COMBUSTION SOURCES

VOLUME III: PARTICLE SIZE

A. INTRODUCTION

The concentration, size, and chemical composition of airborne particles are the three most important properties defining the potential effects, harmful or otherwise, of most particulate dispersions. Automatic measurement of the concentration, specifically the mass concentration, of airborne particles is the subject of Volumes I and II of this report. This volume discusses the automatic measurement of size and size distribution of airborne effluent particles from large coal and oil combustion sources. Chemical composition and its measurement is not a subject of these reports.

The size of an airborne effluent particle plays a very important part in determining its future as an air pollutant. One of the primary purposes for the measurement of particulate effluents is to monitor the potential harmfulness of the emissions so that the degree of control can be evaluated. A continuous measurement of particle concentration or emissions rate is usually not a sufficient indication of the potential harmfulness of particulate emissions. Measurement of the size of the particle greatly improves the estimate of the potential harmfulness.

To comprehend the magnitude of the effect of particle size, consider one microgram of particles that is made up of a single 100 micron (μm) diameter particle with a density of about 2.0 grams per cubic centimeter. Nearly all 100 μm particles are collected by most control equipment on effluent sources. The few 100 μm particles that are emitted to become air pollution settle to the ground quickly, usually within a mile or two of the source. Their settling velocity is about 50 centimeters per second. The settled particles result in such harmful effects as dirty cars, houses, and streets, contamination of soil resulting in harm to nearby farm crops, contamination of nearby lakes and rivers, and the aesthetic degradation of the community. There is almost no direct health hazard to humans from inhalation of such particles because very few reach the person, very few of those that do reach him enter his respiratory system, and nearly all which enter the respiratory system are collected by the entrance nasal passage. The chemically-reactive surface area of 100 μm particles is relatively small compared to the same mass of smaller particles.

If that same microgram of particles is made up of particles 1 μm in diameter, there would be about 1,000,000 of them. Most particulate control equipment in use today probably collects only about half of the 1 μm particles in an effluent stream. Most cyclone collectors collect almost none of these particles while high efficiency

electrostatic precipitators can be designed to collect most of them. The settling rate of 1 μm particles is about 0.05 centimeters per second, almost negligible in many cases. A 1 μm particle does not grow very rapidly by agglomeration with other particles or by condensation of liquids on its surface. Thus, these particles will travel long distances from the effluent source before settling to the ground or depositing onto a surface. A large portion of such particles emitted by effluent sources in industrial areas reach heavily-populated centers where they scatter large amounts of light resulting in reduced visibility and less sunlight reaching the ground, where they coat surfaces with grimy films, and where people inhale them. One μm particles penetrate more deeply into the respiratory system than nearly any other size. The chemically-reactive surface area of 1 μm particles is about 10,000 times greater than an equal mass of 100 μm particles. One μm particles, or slightly smaller, penetrate even the highest efficiency fiber and membrane filters more easily than any other size. Thus, 1 μm particles are a different type of air pollutant than 100 μm particles, and should not be lumped with 100 μm particles for measurement purposes.

Now, if that microgram of particles is made up of 0.01 μm particles, there would be 10^{12} of them. Although no comprehensive study has been made, even the highest efficiency electrostatic precipitator control equipment in use today probably does not collect a significant fraction of these particles. It appears that only high efficiency filters can collect them. Their gravitational settling velocity is about 10^{-5} centimeters per second, completely insignificant when compared with motions caused by forces such as wind, Brownian diffusion (random molecular bombardment), temperature gradients, electrostatic fields and charges, and Van der Waals molecular attractive forces. These particles can grow rapidly by condensation of vapors, resulting in a higher liquid content of the particle. They can also grow by agglomeration with other particles resulting in a lesser number of larger particles. The size distribution of particles in this size range often changes rapidly, making measurements difficult, and resulting in larger particles (0.1 - 1.0 μm) after a period of time. In normal city atmospheres, this growth process requires a few hours. Particles in the size range from 0.01 - 1 μm make up most of the photochemical smog so prevalent in cities like Los Angeles. Brownian diffusion causes most of the 0.01 μm particles to deposit in the upper and middle portions of the respiratory system, causing them to penetrate less deeply than 1 μm particles. These particles are highly reactive, having a surface area about 100 million times greater than an equal mass of 100 μm particles. Particles in the 0.01 - 1 μm range are often the nuclei for raindrops and ice crystal formation. The effects of these small particles has little in common with the effects of 1 or 100 μm particles, and the concentration of such particles should be measured separately.

Combustion effluent sources emit particles over an even broader size range: from about 0.001 to over 100 μm. All portions of the size range are important in defining the pollutant potential of particulate emissions. Prediction and control of photochemical smog formation requires information about the very small

particles (from about 0.001 to 1.0 μm). The study and prediction of meteorological effects such as modified raindrop production also need measurements in this size range. Control of respirable particles requires measurement of particles in the 0.1 - 10 μm range. The range from 0.1 - 10 μm affects visibility most strongly. Control of dust fall near an effluent source requires measurement of the particles larger than about 10 μm. Thus, the need for measurements of particle size over the entire range is established.

The size of a particle is usually defined in terms of a diameter or radius. However, anyone looking at a sample of effluent particles with a microscope realizes that most particles are not spherical and, hence, do not have a well defined diameter. It is difficult, for example, to assign a single characteristic dimension to a rod- or flake-like particle. Many conventions have been used for classifying particles by size with a microscope, such as using one of the following as the characteristic size: the longest dimension, the diameter of a circle with cross-sectional area equal to the particle in question, or the diameter of a sphere with volume equal to the particle in question.

However, the most useful method of classifying particles by size in most air pollution systems is based on how rapidly the particle settles out of the atmosphere. The relative harmfulness of a particle depends on several factors, one of the most important being whether the particle remains airborne long enough to reach high density human populations. Thus, the most reasonable size classifying system places particles in categories depending on their relative settling velocities. Particle size measured in this way is called the aerodynamic size, and is usually referenced to the settling velocity of a sphere with a specific density of 1.0 gram per cubic centimeter. Thus, a particle which settles at the same velocity as a 10 μm diameter spherical particle with specific density of 1.0 gram per cubic centimeter is said to have an equivalent aerodynamic size of 10 μm.

Particles with the same equivalent aerodynamic size, even though with different specific densities and shapes, will have an equal chance of settling to the ground within a given time period. For example, a 6.3 μm spherical particle with specific density of 2.5 grams per cubic centimeter has an equivalent aerodynamic size of 10 μm.

Equivalent aerodynamic size also characterizes the ability of a particle to penetrate into the deepest portions of the human respiratory system after entering the nose. Many of the dynamic properties of airborne particles, such as agglomeration, collision, and reaction rates between particles, depend upon equivalent aerodynamic size.

From the time the particle enters the atmosphere until it becomes firmly attached to a surface, i.e., during its entire life as an airborne pollutant, equivalent aerodynamic size is usually the most useful characteristic size. It is our opinion that, although other methods of classification may be useful in specific cases, for most pollution measurement applications, size classification by aerodynamic methods is preferred.

A look at the equations defining equivalent aerodynamic size will show the important parameters which affect it. The gravitational settling velocity v_s of a spherical particle in air is expressed in terms of particle and air properties by the well-known Stokes equation (e.g., see Ref. 1333, p. 23):

$$v_s = \frac{mg}{3\pi\eta D_p} \qquad (A.1)$$

where

m = mass of the particle

g = gravitational constant

η = viscosity of the air

D_p = diameter of the particle.

Equation (A.1) is valid only at atmospheric pressure and for particles having an aerodynamic diameter larger than about 1 μm diameter. In the molecular slip flow region below 1 μm, the Cunningham slip correction C to the Stokes equation applies. The Cunningham slip correction takes account of the discontinuous nature of particle-molecule collisions when the particle is comparable to the mean free path in size. (See Fuchs[1333], p. 25, for detailed discussion.) Equation (A.1) then becomes:

$$v_s = \frac{mgC}{3\pi\eta D_p}. \qquad (A.2)$$

With particle mass m expressed in terms of particle volume and density γ_p, Equation (A.2) becomes:

$$v_s = \frac{D_p^2 \gamma_p g C}{18\eta}. \qquad (A.3)$$

To calculate the equivalent aerodynamic diameter of a particle which settles with velocity v_s, solve Equation (A.3) for D_p, which then becomes equivalent aerodynamic diameter referenced to the particle density γ_p. Thus, Equation (A.3) defines equivalent aerodynamic size.

We have now briefly discussed some of the various ways of defining particle size. An equally important factor in expressing particle size distributions is how the amount of particles in each size category is expressed. This is called the weighting of the size distribution.

There are many ways to express the amount of particles in each size category. One way often used in expressing atmospheric particle size distributions is the number of particles per unit air volume within each size range. This is called the number concentration size distribution. Other commonly used particle concentration

weightings include particle mass, particle surface area, and particle volume. Rather than expressing the actual particle concentration in numbers, milligrams, square centimeters or cubic centimeters of particles per unit air volume, the concentration weighting can be expressed as a percentage of the total which is contained within each size category. For example, in the case of a particle mass percentage weighting, the result would be a graph showing the percentage of the mass of particles contained within each size category, or more commonly, the percentage of the mass of particles contained by particles larger than (or smaller than) a given size.

Figure 1 illustrates several of the more common ways of expressing a particle size distribution in graph form. All nine graphs in Figure 1 represent the same particle size distribution. Notice that each curve has a different shape or slope, depending on which particulate parameter is represented and on how the investigator chooses to represent it. There are many other ways to plot particle size distribution, each resulting in a curve with a unique shape.

It is not always clear which way of expressing size distributions is most advantageous in any given situation. Each has its limitations. A mass distribution generally emphasizes large particles and deemphasizes or ignores small particles which are important but do not contain significant mass compared to the large particles. A number distribution, on the other hand, emphasizes small particles which are present in large numbers. A number distribution ignores the one or two large particles in a cloud of millions of small ones, even though the one or two large particles may weigh more than the millions of small particles. A concentration distribution shows the actual particle concentration level, an important factor determining particle interaction rates and as essential factor for pollution control monitoring. The percentage distribution, as well as several other distributions, shows quickly, clearly, and without ambiguity, exactly which size range contains the majority of the particles. Although one can usually convert mathematically from one distribution to another, any measurement error becomes magnified with each conversion. One cannot convert from a percentage distribution to a concentration distribution without additionally knowing the total concentration of the particle sample.

Thus, it is important to decide which method of expressing size distribution is most useful for a given application before choosing the size measurement technique. The investigator will then choose a size measuring technique which yields the desired size distribution as directly as possible. Although a strong case can be made for aerodynamic size as the most useful for most air pollution measurements, the choice of the method of expressing particle concentration is not as simple. One must be very careful not to ignore an important range of particle sizes simply because of the choice of particle concentration weighting.

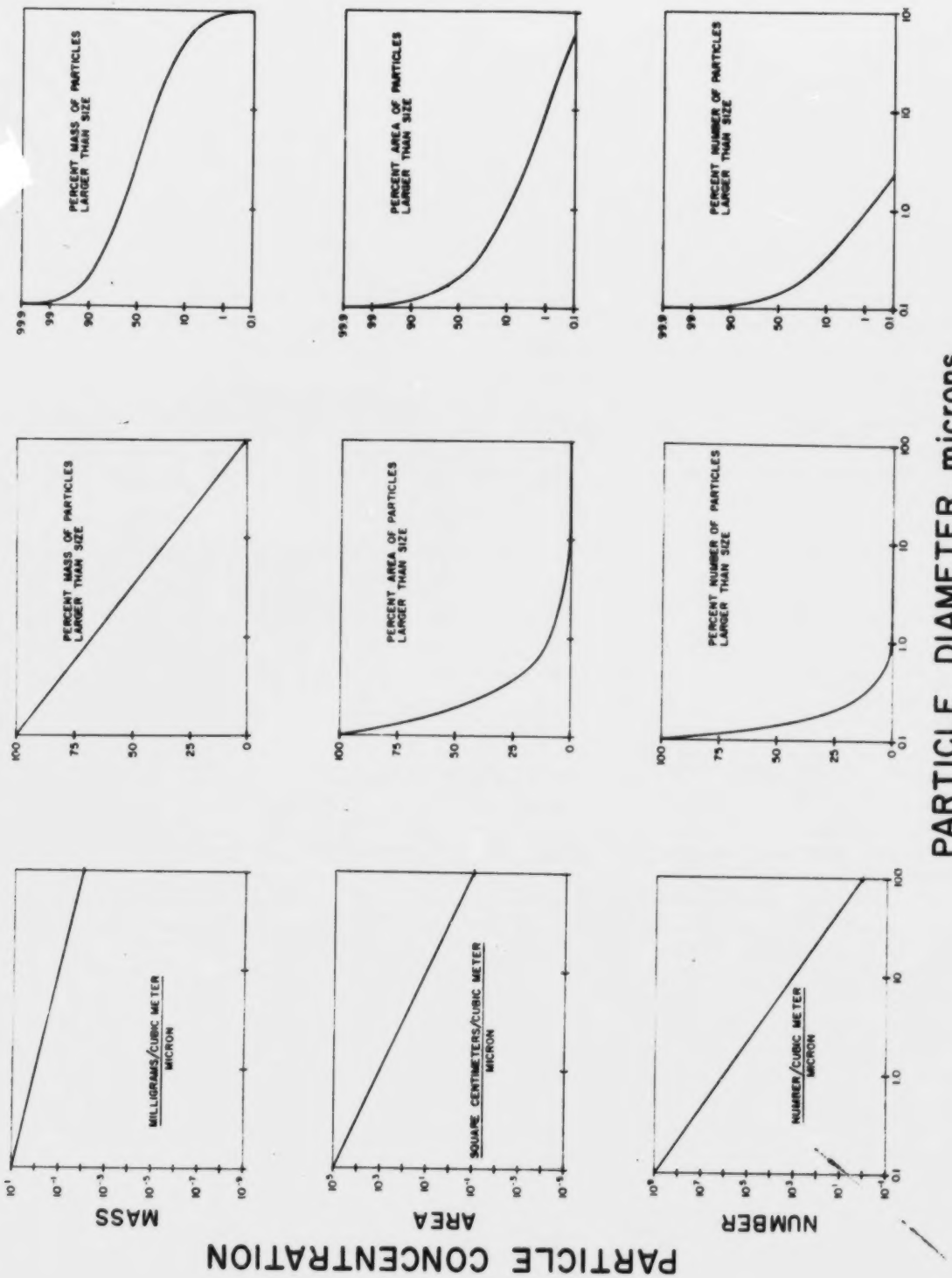


Figure 1. Nine ways of presenting the same particle size distribution. The distribution shown is not necessarily realistic, but is made up entirely of particles in the 0.1 to 100 micron range.

The discussion above is concerned primarily with complete size distributions and methods of presenting them. There are ways of expressing important features of a distribution as single numbers. A common method is to express an average size (usually diameter) accompanied by a number representing the spread in the distribution (usually standard deviation or geometric standard deviation). The range of particle size, meaning the size of the largest and smallest particles in the distribution, is another measure of the spread of a distribution. Other "averages" include the mean, median, and mode of the distribution. The number median and mass median diameters are commonly used. The mass median diameter is the diameter which breaks the distribution into two size ranges, each containing 50% of the total mass.

This discussion has included only a brief summary of the most important aspects of the definition of particle size and size distribution. Any reader contemplating work in this area is strongly urged to refer to a text such as Herdan (Ref. 1357). Many other aspects are covered in Herdan, including details on converting from one distribution to another, how to choose the optimum number of size ranges to cover a size distribution, other ways of presenting size distributions, hints on interpreting a size distribution, etc.

At present, no instrument is available that can measure the complete range of particle sizes in an effluent source. One reason is the inherent problem of the choice of particle weighting discussed earlier. Thus, if the mass size distribution is measured, small particles are ignored, etc. However, every instrument also has practical limitations of size range. Few instruments can cover more than a range of one-two decades in particle size. No instrument with potential for automation can accurately cover more than 2 size decades. Since combustion effluents cover at least 5 size decades (0.001 - 100 μm), either several different instruments must be combined to cover the complete size distribution, or one must choose the size range of primary interest and find a suitable instrument for that range.

In the past, the range of sizes measured in combustion sources was dictated by the available technique. Thus, almost all measurements were of mass concentration in each of several size ranges from about 2 μm to about 100 μm. Particles below 2 μm could not be size classified by the technique and their mass could not be detected in the presence of the larger particles. This has led to the conclusion that there probably is no contribution to the mass emissions by particles below about 1 μm in combustion effluents; however, this has not been documented by direct measurements. In the case of particles above 100 μm, most such particles settled out of the sampling line before reaching the sizing instrument. Thus, most existing data on particles above 100 μm also appears to be inaccurate. Most of the existing particle size data from combustion sources is highly questionable for these reasons.

Sampling statistics also often limit the validity of particle size data, especially number count data. Much of the existing microscopic count size data was obtained using a single microscopic magnification. With most atmospheric and combustion-source aerosols, there are so many small particles that the likelyhood of counting a large particle with this method is small, even if 1,000 - 10,000 particles are counted for a single size distribution. For example, there are usually 1,000 - 10,000 times as many 1.0 μm particles in atmospheric aerosols as there are 10 μm particles. Thus, for a reasonable statistical chance of obtaining an accurate distribution covering only a single order of magnitude of size using a single magnification requires the counting of about 100,000 particles, a formidable task One method of avoiding this problem is to use several magnifications covering the size range of interest. Each magnification should cover no more than a factor of 5 in particle size. Each magnification can then be chosen such that the smallest size of interest is easily detectable and yet, the largest size of interest will be counted enough times to result in a statistically valid distribution. This same statistical limitation also applies to any instrument which counts the number of particles in a distribution. The solution for such instruments is usually to count enough particles to overcome the limitation.

Better sizing instruments must be made available so that measurements will include the entire size range of interest. The increasingly recognized importance of micron- and submicron-sized particles places special emphasis on the small particle No single sizing technique can cover the entire size range. Thus, several techniques will have to be used. The interpretation of the data obtained from several different measuring techniques will be a problem in some cases. However, no method is foreseen that will measure detailed distributions over the entire size range with a single measuring technique.

The remainder of this report discusses specific particle size measuring techniques in detail. The discussions are limited primarily to a basic evaluation of each technique rather than a discussion of exact design details. The reason for this is that most techniques are not developed for application to measurements of combustion effluents, making a discussion of design details rather speculative.

All particle sizing instruments must perform two distinct functions: (1) classify the particles by size and (2) sense the amount of particles within each size range. In some measurement techniques, the two functions can be considered separately and developed hardware may consist of the two distinct components. Section B discusses first classifiers, then sensors, and last, combinations of the two components. It will be seen that most classifiers can be used with most sensors, some combinations having better features than others. Section C discusses sizing techniques which, while performing both functions, does not allow separation of hardware for each function. Throughout Sections B and C, emphasis is placed on the more feasible techniques.

A number of particle sizing techniques exist for powders and liquid slurries. Section D discusses possible application of these techniques to combustion source aerosols. These techniques are deemphasized because of the difficulty in relating the size of the slurry particles to the particles in their airborne state.

Section E discusses a different concept of size monitoring for use in combustion source effluents as well as elsewhere. This concept has strong, practical appeal, but requires more study and a moderate amount of development and testing.

Finally, Section F lists the most important conclusions and summarizes this study.

B. TECHNIQUES WITH SEPARABLE CLASSIFICATION AND SENSING

Many instruments for measuring the size distribution of an aerosol can be broken into two independent components:

1. A classifier which separates the particles into several size fractions, and

2. A sensor which measures the amount of particles within each size range.

Conversely, practical sizing instruments can often be assembled by connecting various classifiers upstream of various sensors. This discussion first considers particle classification techniques, then considers particle sensors, and finally considers the most reasonable combinations of the two.

1. Particle Classification Techniques

This chapter discusses all known particle classification techniques and all known forces which can act on airborne particles. The classification techniques discussed below are:

a. Aerodynamic Classification

   i. Gravitational Sedimentation
   ii. Gravitational Elutriation
   iii. Inertial Impaction
   iv. Centrifugal Spectrometry
   v. Cyclone Separation
   vi. Centrifugal Elutriation

b. Electrostatic Classification

c. Sieve Classification

d. Filtration

e. Brownian Diffusion

f. Other Forces

a. Aerodynamic Classification

When a particle moves with respect to the surrounding air, the force which resists that motion is called aerodynamic drag force. For a spherical particle larger than 1.0 μm diameter moving with a slow, constant velocity through air at atmospheric pressure, aerodynamic drag force F_d can be expressed by the Stokes equation:

$$F_d = -3\pi\eta D_p v \qquad \text{(B.1)}$$

where:

η = viscosity of the gas,

D_p = particle diameter, and

v = particle velocity with respect to the gas.

The negative sign means that the force acts in a direction opposing the motion of the particle with respect to the gas. For particles between 0.1 and 1.0 μm (i.e., about the same size as the molecular mean free path of standard air) and with all other conditions equal to those for Equation (B.1), F_d can be expressed by the Stokes - Cunningham equation:

$$F_d = - \frac{3\pi\eta D_p v}{C} \qquad (B.2)$$

where:

C = Cunningham slip-flow correction.

As D_p becomes large compared to the molecular mean free path, $C \to 1.0$ and Equation (B.2) becomes Equation (B.1). Equation (B.2) is valid with reasonable accuracy for particles with $0.1\ \mu m < D_p < 50\ \mu m$, covering much of the range of interest for effluent particles. The literature (e.g., Reference 1333, pp. 21-34) discusses variations of F_d for other conditions and for D_p other than the above range, and lists values of C for various conditions.

The next six sections discuss different ways in which the aerodynamic drag force can be used to separate particles into size fractions.

i. Gravitational Sedimentation

One of the simplest ways to use the aerodynamic drag force to classify particles is to allow the particles to settle downward through air by means of their own weight. In this case, the particle quickly assumes a constant velocity, called the terminal velocity, when the downward force of gravity ($F_g = mg$) just equals the upwards force of aerodynamic drag (Equation B.2). Equating these forces and solving for velocity, one obtains:

$$v = - \frac{mgC}{3\pi\eta D_p} \qquad (B.3)$$

where:

m = particle mass, and

g = gravitational constant.

Expressing m in terms of particle volume and density, Equation (B.3) becomes:

$$v = -\frac{\gamma_p D_p^2 Cg}{18\eta} \qquad (B.4)$$

where:

γ_p = density of the particle.

Equation (B.4) shows that, for particles of constant density, the settling velocity increases as the square of the particle size. Thus, the length of time t_ℓ it takes a particle to settle a given distance ℓ decreases with an increase in the particle size:

$$t_\ell = \frac{\ell}{v} = \frac{18\eta\ell}{\gamma_p D_p^2 Cg}. \qquad (B.5)$$

In terms of hardware, a sedimentation size classifier is shown schematically in Figure 2. The particles settle through the laminar clean air streamlines and deposit onto the bottom of the chamber. The sharpness of the size classification depends on the height of the aerosol entrance duct with respect to the average settling distance, ℓ, and on the velocity profile of the aerosol and clean air flow.

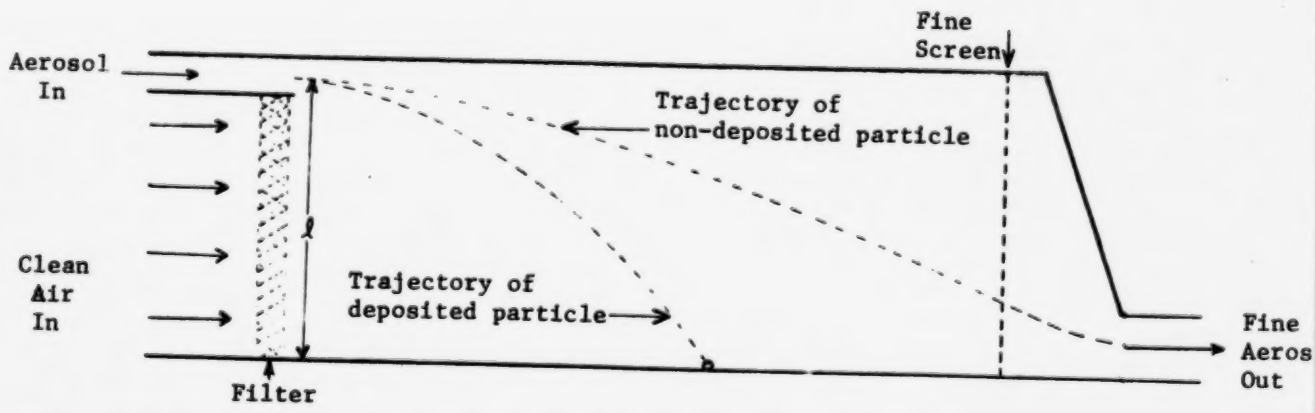


Figure 2. Schematic sedimentation size classifier with horizontal air flow.

If operated upstream of a concentration sensor, the sedimentation size classifier would collect particles larger than a given size, and particles smaller than that size would pass through to the sensor. The particle size cutoff could be decreased by reducing the settling height ℓ or by decreasing the horizontal flow velocity through the classifier. The former results in a less sharp size cutoff and the latter results in greater interference by convective currents. Thus, any classifier of this type can be designed for only a narrow range of adjustable particle size cutoffs, probably one order-of-magnitude at most. The overall practical size range for sedimentation classifiers is from about 1.0 μm to about 50 μm. The lower size limit is set by the practical limitations on the smallest values of ℓ and air flow rate, as well as by interference by convective currents. The upper size limit is set by the difficulties in introducing large particles into the entrance without losing them.

The sedimentation classifier dilutes the aerosol which passes through by the ratio of clean air to entering aerosol. The upper concentration of entering aerosol is not a limiting factor for effluent aerosols.

The Hexhlet dust sampler manufactured by

C. F. Cassella & Co., Ltd.
Regent House, Fitzroy Square
London W1, England

uses a simplified sedimentation classifier which consists of parallel plates through which the aerosol passes. There is no clean air sheath, making the classification considerably less sharp, but making operation easier. Other authors report other models of sedimentation classifiers, often called horizontal elutriators.[274,834,1299,638,833,912]

ii. Gravitational Elutriation

Elutriation is similar, in many respects, to sedimentation. The principle of a gravitational elutriator is shown schematically in Figure 3. Laminar air flows vertically within the elutriation tube. Aerosol is introduced at the bottom of the tube. Large particles, i.e., those with settling velocities (Equation B.4) greater than the vertical air flow velocity, will be carried out with the exhaust. The particle cutoff size is determined by the vertical air velocity in the tube.

The major factor causing degradation of the sharpness of the particle size cutoff is the shape of the air velocity profile within the tube. Ideally, the air velocity profile would be flat at all points. In practive, however, a boundary layer forms at the tube wall, allowing small particles to settle to the bottom of the tube

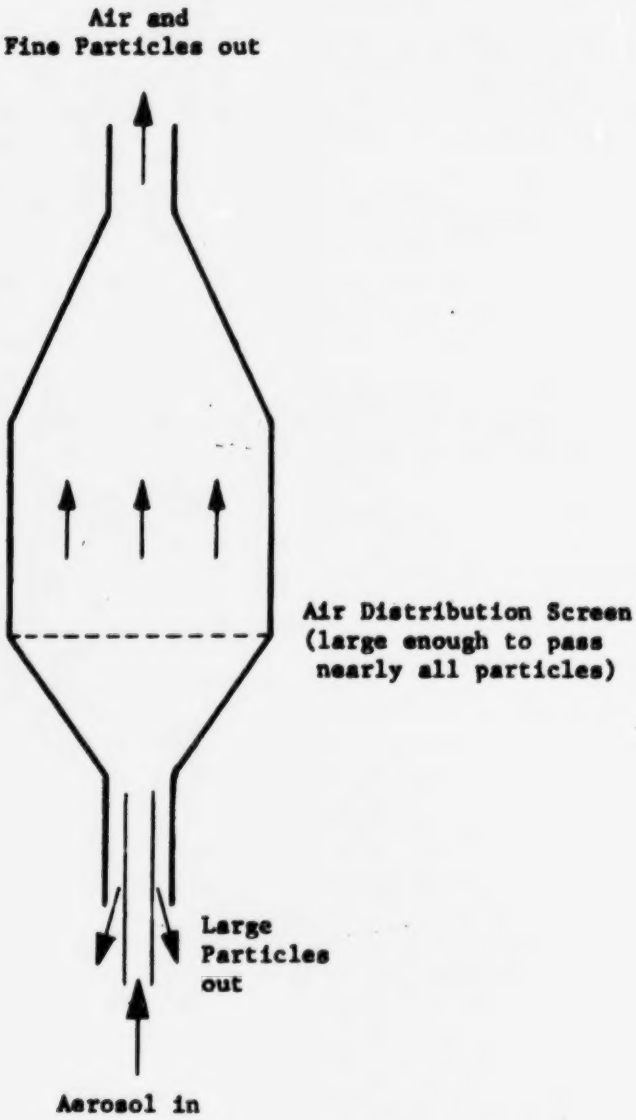


Figure 3. Principle of a gravitational elutriator.

through the boundary layer. Convective currents caused by thermal gradients within the elutriator also modify the velocity profile. The ability to overcome these two related problems determines the ultimate sharpness of the particle size cutoff in practive. The concentration levels within the elutriator must be low enough so that large particles settling downward do not intercept appreciable numbers of smaller particles. The applicable size range of elutriation is about 1 to 100 μm. Other limitations are similar to those with the sedimentation classifier.

Several authors have considered gravitational elutriation in more detail.[638,833,912,1069,1333(p. 42,43)].

A commercial gravitational elutriator for size classification of powders is manufactured by:

Geoscience Instruments Corporation
435 East 3rd Street
Mount Vernon, New York 10553.

The advertised size range is 5 to 100 μm. This unit would not lend itself to the sizing of stack effluent particles on a continuous basis without considerable modification.

Gravitational elutriation size classification is a definite candidate for application to effluent aerosols. Gravitational elutriators operate over the approximate size range of 1 to 100 μm, and may have the ability to classify even larger particles because higher velocity in the entrance tube allows the larger particles to enter the sedimentation classifier. Several elutriators designed for different size cutoffs would probably be necessary to cover the entire 1 to 100 μm range. A strong feature of this classifier is that it results in an aerosol classified by aerodynamic equivalent size.

iii. Inertial Impaction

A third method of using aerodynamic drag to classify aerosol particles is inertial impaction. Figure 41[340] shows an impactor schematically. A flat plate is located at the exit of a nozzle, perpendicular to the air jet. Air is sucked through the nozzle and must turn a sharp corner to pass around the flat plate. Because of their inertia, sufficiently large particles cannot turn the corner, and therefore hit the plate. Smaller particles do not have enough inertia to cross the air streamlines and are carried along with the air stream.

As particles cross the air streamlines in an impactor, the force which resists that motion is aerodynamic drag force expressed in Equation (B.2) with v being the component of the particle velocity perpendicular to the streamlines.

When discussing impactors, it is convenient to define a parameter known as Stokes number:

$$Stk = \frac{\gamma_p C v_o D_p^2}{9\eta W} \qquad (B.6)$$

where:

Stk = Stokes number,

v_o = average air jet velocity, and

W = jet width (rectangular jet) or diameter (round jet).

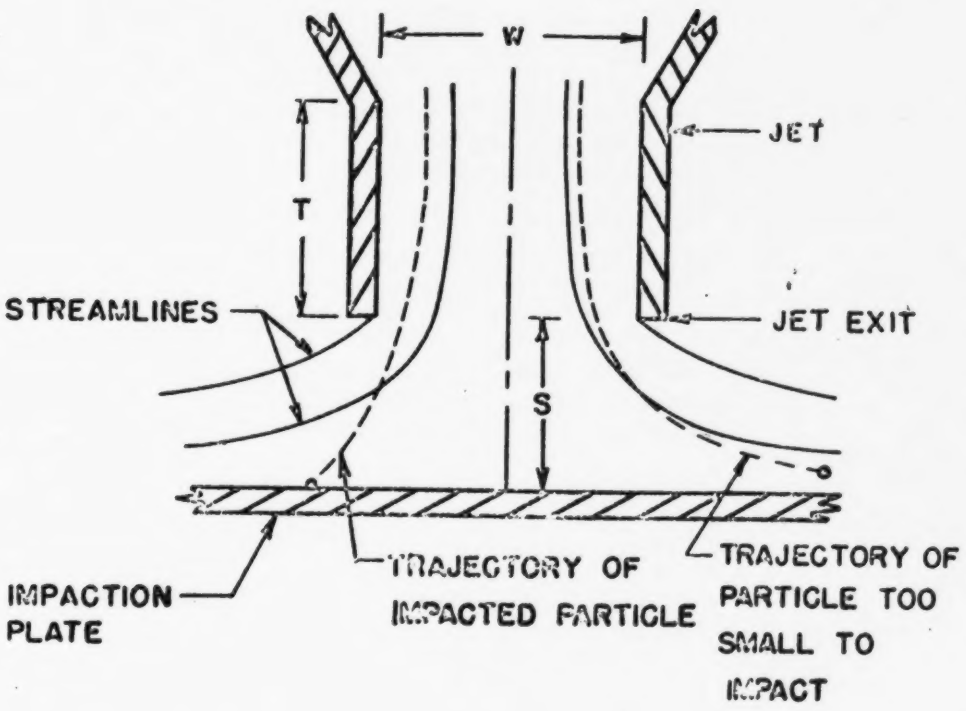


Figure 4. Schematic of an impactor showing particle trajectories.[1340]

A dimensionless particle size is defined as $(Stk)^{1/2}$. Particles with the same Stokes number have an equal chance of being collected by a given impactor.

Ideally, an impactor should collect all particles larger than a certain cutoff size and all smaller particles should escape as shown by the dotted line in Figure 5 [1340] In practice, however, impactors have a characteristic "S" - shaped efficiency curve.

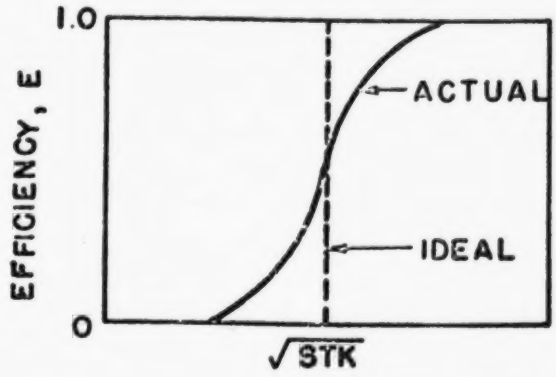


Figure 5. Typical ideal and experimental collection efficiency curves of an impactor.[1340]

There are several reasons for this nonideal operation. These reasons have been investigated in considerable detail in the literature (see especially, References 1333 (pp. 151-159) and 1340), including:

a) the velocity profile at the jet exit is not flat giving particles near the center of the jet greater inertia than particles near the jet walls,

b) a boundary layer forms along the plate deflecting particles which are near the edge of the jet more than particles which are near the center line,

c) the high jet velocities needed to collect small particles blow some of the larger particles off the plates or cause them to bounce off,

d) some weakly-bound agglomerates of smaller particles break up while passing through the high shear forces within the jet or while striking the surface, and

e) with rectangular jets, the ends of the jet act like a round jet impactor while identical particles within the central areas have significantly different Stokes numbers.

Marple[1340] performed a careful theoretical and experimental study of both round and rectangular jet impactors and recommends the jet operating conditions shown in Table B.1 as the optimum for obtaining a sharp particle size cutoff. The dimensions S, W, and T refer to Figure 4 and Re is the Reynolds number based on the average jet velocity and the jet diameter or width. Figure 6[1340] shows the impaction efficiency as a function of $(Stk)^{1/2}$ for each of the two optimum conditions outlined in Table B.1. The rectangular impactor must be much longer than it is wide. Re can vary from 500 to perhaps 100,000 without significantly changing the efficiency relationship. Values of S/W greater than those shown in Table B.1 (up to S/W = 5) affect

Table B.1 Optimum jet configurations.[1340]

Jet	S/W	T/W	Re
Round	1/2	1	3000
Rectangular	1	1	3000

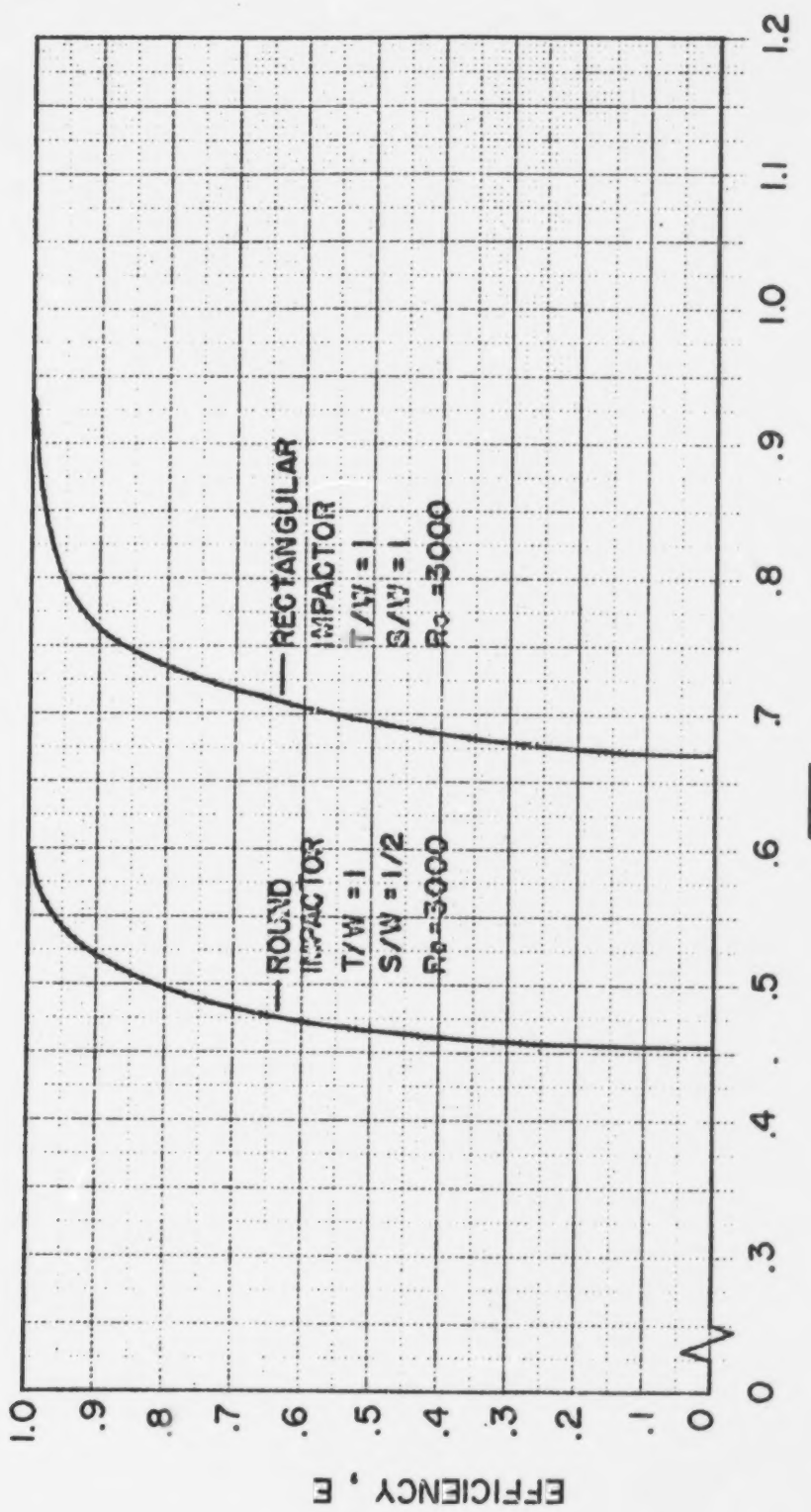


Figure 6. Comparison of efficiency curves for the optimum round and rectangular impactors.[1340]

the efficiency only slightly, but values less than those shown cause efficiency to change quite drastically. In several reported tests,[1340] varying the throat length from T/W = 1 to T/W = 10 did not influence the efficiency curve significantly.

A number of other investigators have studied both round and rectangular impactors. Tables B.2 and B.3[1340] catalog the operating conditions of each study.

Particles can be impacted into an air void[996,1383] rather than onto a flat plate as described earlier. In this case, the impaction "surface" consists of static air. The problem of particle blowoff is eliminated by the use of a void. Large amounts of particles can be impacted and collected for subsequent analysis. Particle sensors can sample either the large-size fraction (from the void) or the small-size fraction (non-impacted particles). Although this technique appears to offer several significant advantages over flat-plate impaction, few models have been built and little experimental data has been found. Bird & Tole Ltd., Bledlow Ridge, High Wycombe, Bucks, England, manufactures a void impactor (called a cascade centripeter) based on the design reported in Ref. 996.

Several impactors are often placed in series, each succeeding stage having a smaller critical Stokes number and thus collecting smaller particles than the preceding stage. The combination of these impactors is called a cascade impactor.[948,995,996,1002] One of the most commonly used methods of measuring the distribution of particle mass as a function of aerodynamic particle size in the 0.2 - 30.0 μm range is to classify and collect particles with a cascade impactor, and then weigh the amount of material collected on each impaction plate. This technique has been used for measuring the size distribution of particles in effluent ducts. The primary features of this technique are (1) aerodynamic size classification and (2) classification of the particles inside the effluent duct at the conditions that exist in the effluent stream. Equipment designed for stack sampling is commercially available from:

2000 Inc. (modified Andersen impactor)
5899 South State Street
Salt Lake City, Utah 84107

Monsanto Company (modified Brink impactor)
800 N. Lindberg Boulevard
St. Louis, Missouri 63166

Table B.2. Experimental studies of rectangular impactors.[1340]

Ref. No.	Reference	S/W	$Re = \frac{\rho D_n V_o}{\mu}$	Pressure (atmospheres)	Type*	Special** Studies	Aerosol
1363	MAY (1945)	1/2-1	1400-2700	1	C(4)	a-b	Windborne
1002	LIPPMAN (1959)	1/2-1	1400-2700	1	C(4)	a	Uranium oxides
1364	WELLS (1967)	.46-.69	1400-2700	1	C(4)		Plutonium & Uranium oxides Polystyrene spheres
1371	DAVIES et al.(1951)		1400-2700	1	C(5)	a-b	Coal dust
1365	SONKIN (1946)		3000-5000	1	C(4)		Glycerol-water-methylene blue solution
1366	LASKIN (1949)			1	C(4)		Uranium compounds
1367	WILCOX (1953)		1800-6500	1	C(5)		
1368	RANZ & WONG(1952a)	1-3	250-16,500	1	S		Glycerol
1369	RANZ & WONG(1952b)	1-3	250-16,500	1	C(4)		Glycerol, Ammonium chloride & Sulfuric Acid
1370	STERN et al.(1962)	.3-1	50-3500	.03-.25	S		Polystyrene spheres
29	LUNDGREN (1967)	1	600-6000	1	C(4)		Polystyrene spheres Uranine dye & Glass beads
1372	MERCER & CHOW (1968)	3/8-5	1200-7000	1	S		Polyvinyltoulene spheres

*S - single stage impactor

C(n) - cascade impactor (number of stages)

**a - wall loss studies

b - particle bounce studies

Table B.3. Experimental studies of round impactors.[1340]

Ref. No.	Reference	S/W	Re = $\frac{\rho D_n V_o}{\mu}$	Pressure (atmospheres)	Type*	Special** Studies	Aerosol
1368	RANZ & WONG(1952a)	1-3	650-22,000	1	S		Glycerol
957	BRINK (1958)	3	1400-6900	1	C(5)		Sulfuric acid
1373	PILCHER et al.(1955)	3/8	1200-12,000	1	C(6)		Dibutyl Phthalate & Polystrene spheres
294	MITCHELL & PILCHER (1959)	3/8	1200-12,000	1	C(6)	a	Dibutyl Phthalate & Polystrene spheres
1370	STERN et al. (1962)	1/3-3		.02-.25	S		Polystrene spheres
1374	MCFARLAND & ZELLER (1963)	.34-1	18-650	.0013-.02	S-M	b	Methylene blue & Uranine dye
1375	ZELLER (1965)	.34-1	18-650	.0013-.02	C(2)-M	b	
1376	ANDERSEN (1958)	2-10	80-380	1	C(6)-M	a-b	Carnauba wax & Airborne Microorganisms
1377	ANDERSEN (1966)	2-10	80-380	1	C(6)-M		Carnauba wax
154	FLESCH et al. (1967)	2-10	80-380	1	C(6)-M		Methylene blue dye & Polystrene spheres
685	PARKER & BUCHHOLZ (1968)	2-10 .35-4		.05-1	C(6)-M C(6)-M	a-b	Sodium chloride, PbI_2, $CsNO_3$, Uranine & Methylene blue plus Uranine
1378	MERCER & STAFFORD (1969)	3/8-10	600-7000	1	S	b	Polystrene spheres
1379	MCFARLAND & HUSAR (1967)	1-1.5	1500-1900	1	C(4)-M	b	Dye particles
1380	MERCER et al.(1970)	1-2	90-1300	1	C(7)	a	Cesium chloride

*S - single stage impactor
C(n) - cascade impactor (number of stages)
M - multiple jet

**a - wall loss studies
b - particle bounce studies

Cascade impactors can also classify particles within effluent streams which have been pre-conditioned, e.g., by dilution and/or cooling. Commercial models which might prove useful for conditioned effluent streams are manufactured or marketed by:

Aerostatics Instrumentation & Research (modified Andersen impactor)
1081 East 2200 North
Logan, Utah 84321

Environmental Research Corporation (Lundgren impactor)
3725 North Dunlap Street
St. Paul, Minnesota 55112

Monsanto Company (Brink impactor)
800 N. Lindberg Boulevard
St. Louis, Missouri 63166

Scientific Advances, Inc. (Battelle impactor)
1400 Holly Avenue
Columbus, Ohio 43212

2000 Inc. (Andersen impactor)
5899 South State Street
Salt Lake City, Utah 84107

Union Industrial Equipment Corporation (Unico impactor)
150 Cove Street
Fall River, Massachusetts 02720

Willson Products Division, ESB Incorporated (Cassella impactor)
2nd & Washington Streets
Reading, Pennsylvania 19603

None of these commercial cascade impactors has an automated deposit sensing or particle concentration sensing method. All are intended to collect a classified sample for subsequent analysis.

The operable size range for cascade impactors in controlled laboratory tests is generally, at best, from about 0.2 to 30 μm diameter, assuming particle density of 1.0 to 2.0 grams per cubic centimeter and nearly spherical shape. The lower limit is set by the difficulties imposed by:

a) very small nozzles which are difficult to drill and tend to plug easily,

b) high jet velocities resulting in some particle blowoff,

c) reentrainment of deposited particles limits the amount of sample which can be collected, and

d) the small weight of small particles cannot be weighed in the presense of the large tare weight of the impaction plate.

The upper size limit can be larger than 30 μm depending on the type of particle and the stickiness of the impaction surface. However, such problems as particle deposition in the entrance regions of the impactor, blowoff of previously-deposited particles, and bounce of impacting particles, usually impose a practical upper size limit.

The lower size limit can be extended by low pressure impaction for some applications. A major problem is the vaporization of particulate materials by the low pressure. Further testing and development is necessary to determine whether low pressure impaction is practical for stack effluents.

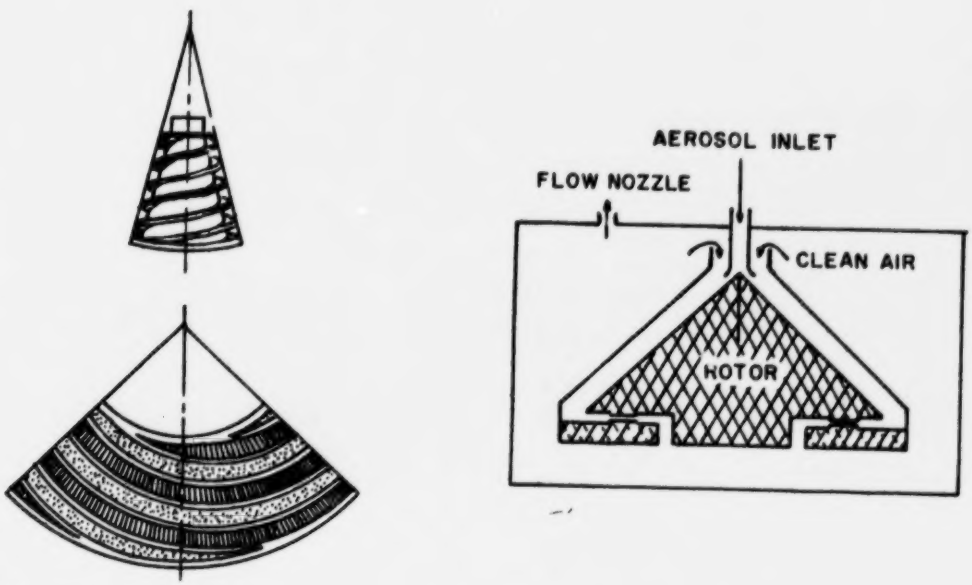
A special case of low pressure impaction, often called an aerosol beam, uses a sonic nozzle with a very low downstream pressure (<0.01 atmsophere). After particles pass through the sudden expansion region just downstream of the nozzle, they are affected very much less by fluid drag forces than in the atmospheric case. One study has looked at the pattern of particulate deposit on a target placed as several distances downstream of the nozzle.[1273,1361] Another study looked at stop distances of the particles in the aerosol beam.[1362] Much work remains to be done to understand aerosol beams. It is not clear how the principle can be utilized for particle size classification. One possible application may be to use the aerosol beam technique to accelerate particles to a constant, known velocity and then use a sensitive momentum transducer (e.g., see Ref. 252) to measure the mass of individual particles. Much work remains to determine if this technique, or any other aerosol beam technique, is practical for sizing micron-sized particles.

Impactors, especially cascade void impactors, are definitely prime candidates for size classifying particles in stack effluents over the size range from about 0.2 to 30 μm. Features include aerodynamic size classification and the ability to classify particles at nearly any environment condition including in-stack conditions. Cascade impactors have been investigated extensively both theoretically and especially in the laboratory. They have been used to classify stack effluent particles with mixed results. Impactors appear to adapt easily to several particle sensing techniques.

iv. Centrifugal Spectrometry

A fourth method of using aerodynamic drag to classify aerosol particles by size is centrifugal spectrometery.[1333 (pp. 123-126), 123, 290, 354, 369, 546, 505, 649, 818, 925, 1119, 1120, 1341, 1342, 1343] This technique is equivalent to gravitational sedimentation except that centrifugal acceleration speeds the process allowing its application to small particles in the 0.03 - 3.0 μm equivalent aerodynamic diameter range.

Figure 7[649] shows the principle of operation of 2 centrifugal spectrometer designs. In the first design, aerosol passes through a spiral-shaped channel which rotates about its axis. Centrifugal acceleration pushes particles radially toward the outer wall of the channel while aerodynamic drag force (see Equation B.1) resists the radial motion of the particles. The effective radius of the spiral channel increases as the aerosol passes through the spectrometer. Large, heavy particles deposit near the inlet where the centrifugal acceleration is low, while small particles deposit near the exit under the influence of high centrifugal acceleration. The spectrometer is normally precalibrated using aerosol particles of known size and noting the position of their deposit on the outer wall of the channel. The second design utilizes a sheath of clean air between the aerosol stream and the deposit surface. The clean air sheath improves the resolution of the spectrometer by forcing all particles to travel nearly the same radial distance before being deposited on the outer wall of the channel.



(1) Spiral design

(2) Sheath air design

Figure 7. Two centrifugal spectrometer designs.[649,1119]

This results in considerably sharper size classification than the first design, but requires lower aerosol sampling rates.[649,1119] The models which have been built used various types of driving motors and bearing systems to allow high centrifugal speeds without vibration. A commercial version of Stober design is marketed by:

Ivan Sorvall Inc.
(street address unknown)
Norwalk, Conn. 06856

It is difficult to imagine an automatic sensing technique for use with centrifugal spectrometry. Additional problems for application to stack effluents is the limited size range (essentially submicron) and the small amount of material which can be collected. This technique has seen considerable application in research studies of laboratory-generated and atmospheric aerosols, and may be useful for some research on stack effluents. However, its application to routine, automatic stack effluent monitoring is doubtful.

v. Cyclone Separation

A fifth method of using aerodynamic drag force to classify aerosol particles by size is the cyclone separator.[1333(pp.126-135), 1334, 1335,1216,675.] Figures 8 and 9 [1333] show the principle of operation of a cyclone. Aerosol enters the rectangular inlet tube A and pa[illegible]s into the cylindrical part of the cyclone where it acquires a spiral [illegible]tion. Air spirals downward along the outer wall of the cylinder, throwing large particles against the wall where they can slide to the bottom of the cyclone. When the air reaches the bottom of the cyclone, it ascends an inner spiral to exhaust through the upper axial tube C. Small particles are carried out by the exhaust air stream. Large particles can be collected for analysis from the bottom of the cyclone.

Figure 8. Cyclone.[1333]

Figure 9. Motion of gas in a cyclone.[1333]

Cyclones are used industrially as dust collectors on large effluent streams. They are used in aerosol sampling as "respirable" size range separators. In this application, a small cyclone separates the large particles from the air stream, presumably simulating the upper passages of the human respiratory system. The aerosol which gets through the cyclone, containing only small particles, then simulates the aerosol which penetrates deeply into the respiratory system. These small particles are generally collected for analysis on a second stage consisting of a high-efficiency filter. Figure 10 shows the "respirable dust" curves which the cyclone attempts to simulate.[1052] One of the curves was first developed at a conference at Los Alamos Scientific Laboratory of the U.S. Atomic Energy Commission[1335] and was modified and adopted as a standard by the American Conference of Governmental Industrial Hygienists in 1968.[1334] The other curve on Figure 10 was defined earlier by the British Medical Research Council.[1052] The aerodynamic diameter in Figure 10 is based on a particle density of 1.0 gram per cubic centimeter. The vertical axis is percent of respirable dust by weight of the particles.

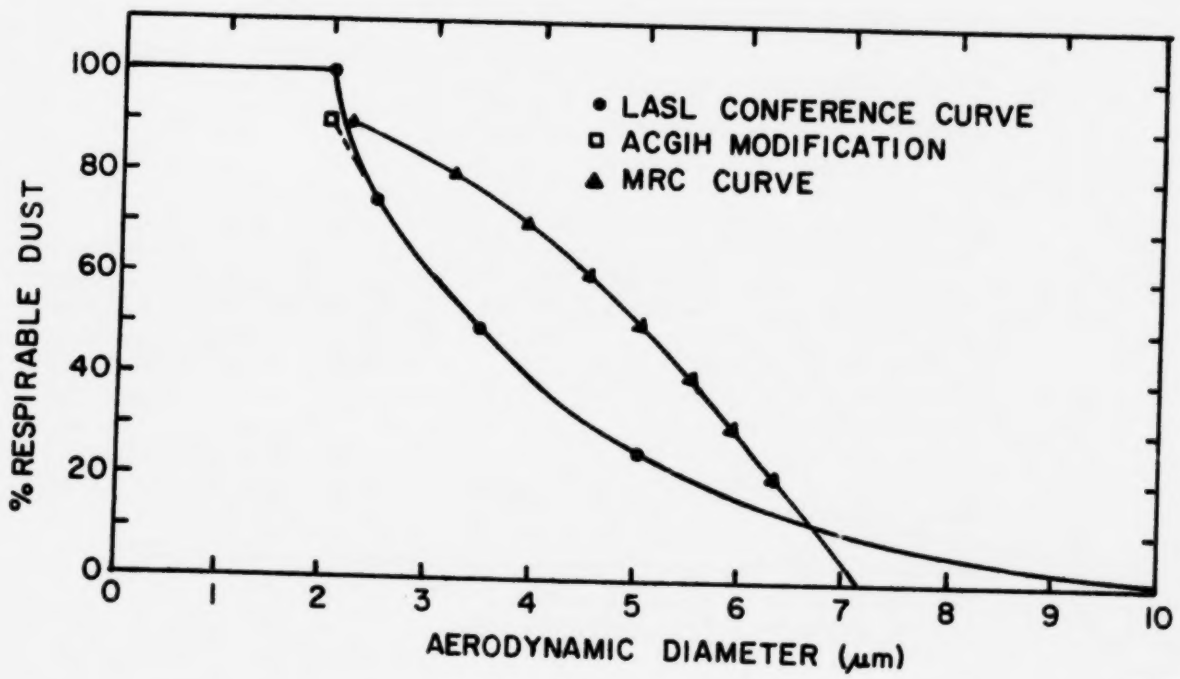


Figure 10. "Respirable dust" curves.[1052]

The relationship between the size of collected particles and the dimensions and operating parameters of a cyclone can be approximated by:[1333 (p. 129)]

$$D_{p,min} = 3 \left(\frac{\eta R_2}{\pi v_o \gamma_p S}\right)^{1/2} \qquad (B.7)$$

where:

$D_{p,min}$ = diameter of the smallest collected particle,

η = viscosity of air,

R_2 = radius of the outer cyclinder (see Figure 8),

v_o = average inlet duct velocity,

γ_p = particle density, and

S = number of turns of the outer spiral in the cylindrical part of the cyclone.

The difficulty in using Equation B.7 is in evaluating S. In most practical cyclones, $1 < S < 3$. Equation B.7 shows that for any given cyclone, an increase in v_o results in the collection of smaller particles. Practical cyclones can be designed such that $D_{p,min}$ is from about 0.5 to 20 µm.

It is not easy to analyze cyclones mathematically. In fact, most cyclones have been designed by use of experimental data. Factors which influence the cyclone performance are the level of turbulence in the cylinder, the relative size of the inlet and exhaust (and thus the inner and outer spirals), redispersion of particles which have struck the wall, the shape of the particles, pulsations in air velocity, the dust concentration level, and the roughness of the cylinder walls. The flow resistance through the cyclone increases roughly as v_o^2. Although some cyclones have been operated successfully in the inverted position, it is important to define the orientation of the cylones. Cyclones, should always be operated with the large particles moving downward unless its operation in an alternative position is carefully investigated. Reference 675 reports the results of an experimental evaluation of cyclone operating conditions.

A set of six identical cylones, each operated at a different flow rate, has been used recently to measure atmospheric particle size distribution in 6 size categories ranging from about 1 - 12 µm.[1354] Walter C. McCrone Associates, Chicago, is currently investigating the applicability of cascade cyclones to size distribution measurements in stacks under contract to the Environmental Protection Agency.

Cyclones are a definite candidate for effluent particle size classification because of the operable size range, the ease of continuous operation, and because the size classification is aerodynamic. The large particles can either be collected continuously for analysis or can be eliminated continuously. As will be seen later, cyclones adapt easily to the inlet of particle sensing instruments, making automatic sensing of "respirable" range particles a relatively simple task. A single cyclone has a limited operable size range. Cyclones have already found application to separating the nonrespirable particle fraction from an air stream so that the respirable fraction can be analyzed.

vi. Centrifugal Elutriation

Another particle size classifying method usind aerodynamic drag force is centrifugal elutriation. This method, usually known as the Bahco method, is often used to classify fly ash effluent particles by size after they have been collected from the effluent stream.[1331,1332,208]

Figure 11[1332] shows the principle of operation of this method as sold commercially for powder sizing. The entire assembly except components 1 - 6 which make up the powder feeder assembly, rotates about a vertical axis. Clean air enters past the throttle nut 13, past the symmetrical disks 11, through the sifting chamber 10, radially toward the axis and then outward through the fan vanes 8. Particles enter the device through the feed nozzle 6 and enter the air stream through the rotary duct opening 9. Large particles are carried outward by centrifugal force and are collected in the catch basin 12. Small particles are carried with the air stream and emerge through the fan vanes 8 where they impact on the inner wall of the rotor casting 7. Thus, the classification results in 2 size fractions, one with particles larger than the cutoff size and one with smaller particles.

The size cutoff can be varied over a range of sizes by changing the throttle nut 13 position by means of throttle spacer 14. This changes the amount of air passing through the device and, in effect, changes the aerodynamic drag force acting on the particles. To measure the size distribution, the operator begins with the smallest size cutoff, runs an analysis, weighs the large fraction which collects in the catch basis 12, and then reruns the large size fraction with a somewhat larger size cutoff setting. This is repeated as many times as necessary.

The ranges of sizes on the commercial unit is from about 50 μm down to 1 or 2 μm. The lower limit is set by the impaction efficiency of particles onto the rotor casting 8. Particles below a certain size will pass out with the air stream and not be collected with the fine fraction. With appropriate design, the fraction which is not collected on the rotor casting 8 could be collected on a filter, resulting in a measurable fraction of small particles. However, the difficulty in collecting small particles is a serious limitation for particles below perhaps 5 μm or for distributions which contain significant mass fractions below this size.

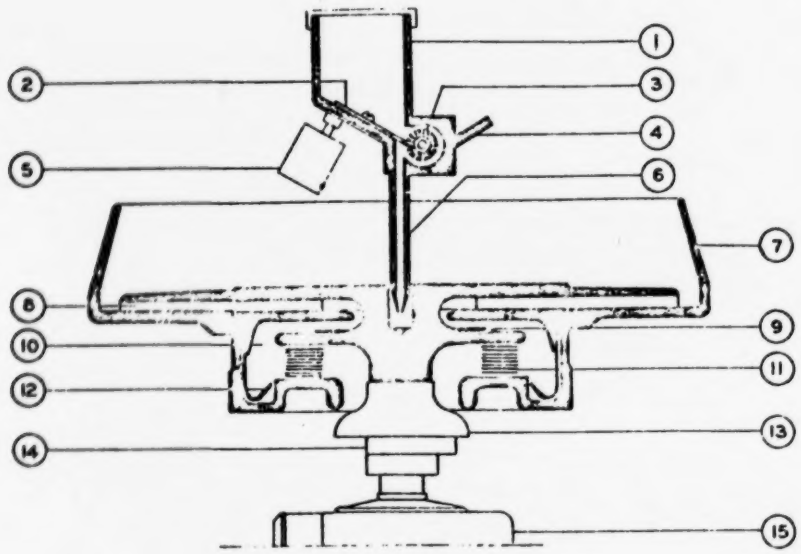


Figure 11. Cross-sectional diagram - 1. hopper, 2. spring plate, 3.brush, 4. orifice tube, 5. vibrator, 6. feed nozzle, 7. rotor casting, 8. fan wheel vanes, 9. rotary duct opening, 10. sifting chamber, 11. symmetrical discs, 12. catch basin, 13. throttle nut, 14. throttle spacer, 15. motor.[1332]

Another factor affecting the classification of any particles which must be resuspended from a powder state is the agglomeration and/or fractionation of particles. This is especially important for smaller particles in the micron size range or smaller. Small particles often adhere to larger particles and are classified with the bigger particles. Thus, it may be desirable to investigate the operation of the centrifugal elutriator on the suspended effluent particles as they emerge from the stack. This may be possible with a redesigned system.

The quality of the classification also depends on the type of air flow through the classifying regions and how the particles are introduced into this region. The turbulence level, boundary layer formation, and the geometry of the particle entrance region are all important. Complete analysis of the existing units is beyond the scope of this report. Such analysis could certainly result in improved performance,but considerable performance testing would be required to evaluate the operation of any such device.

This technique has been accepted by the ASME for measuring the size of collected fly ash powder samples.[239] The Bahco apparatus was used to obtain much of the size information on fly ash which is reported in the literature, including much of the data reported in Volumes I and II of this report.

The commercial version of the centrifugal elutriator for powders is manufactured by:

Harry W. Dietert Company
9330 Roselawn Avenue
Detroit, Michigan 48204

This company holds the American license from the Swedish Company: AB Bahco.

The centrifugal elutriation technique is a candidate for effluent particle classification. Although the technique is commonly used for sizing fly ash particles, the present technique requires the collection of a fly ash sample and redispersing the particles for the measurement. This process is subject to large errors when submicron or micron-sized particles are present in significant amounts. The lower size limit of the present apparatus is in the 2 - 5 μm range. It would seem that this technique could operate with the feeding of airborne particles directly into the apparatus. Such a technique would probably require considerable redesign, but could result in a reasonable classifier for the 1 - 60 μm (approximate) range. This technique results in aerodynamic equivalent diameter classification with its many advantages. This technique appears to offer no significant advantage over cyclones and impactors and is generally more expensive.

b. Electrostatic Classification

An aerosol particle which carries an electrical charge can be acted upon by an electric field. The force acting on such a particle is expressed:

$$F_e = n_p \, e \, E \qquad \text{(B.8)}$$

where:

F_e = force acting on the particle because of its electrostatic charge,

n_p = number of elementary charges attached to the particle,

e = elementary unit of charge, 1.6×10^{-19} coul/elementary charge, and

E = electric field intensity.

This force causes the particle to move through the gas in a direction determined by the polarity of the field and the polarity of the charge on the particle. The force resisting this motion is aerodynamic drag force, expressed in Equation (B.1). Equating these two forces, one can define the final speed attained by the particle:

$$v = \frac{n_p \, e \, E}{3\pi\eta D_p C}. \qquad \text{(B.9)}$$

Another term often used in electrostatic theory is the electrical mobility of a particle Z_p defined:

$$Z_p = \frac{v}{E} = \frac{n_p e}{3\pi\eta D_p C}. \qquad (B.10)$$

Figure 12 shows the mobility of singly-charged particles in standard air as a function of particle diameter D_p. The mobility of multiply-charged particles is simply the value shown in Figure 12 multiplied by the number of elementary charges n_p. The electrical mobility of a particle is the velocity of that particle when acted upon by an electric field of unit intensity.

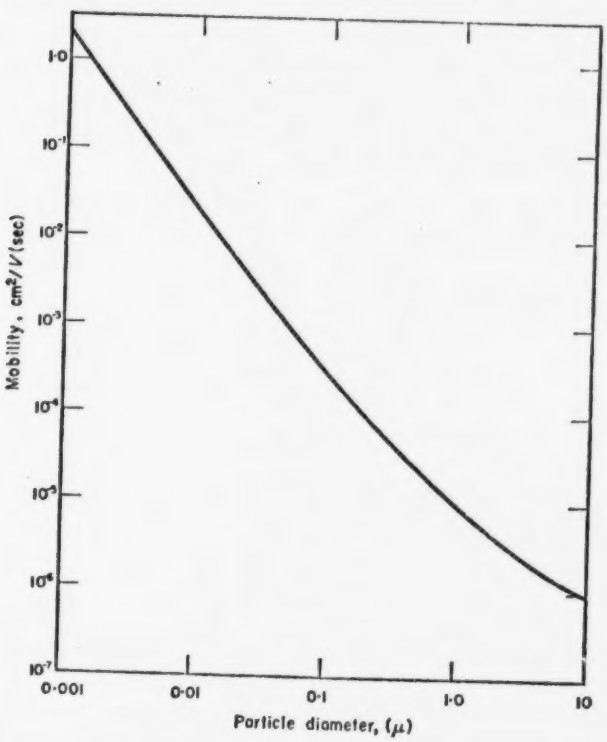


Figure 12. Electric mobility of singly-charged particles at NTP.[211]

If aerosol particles can be electrostatically charged such that n_p is a reproducible function of particle size D_p, then a mobility classification is also a particle size classification. Several mobility classifiers are shown in Figure 13.[1211] The mobility classifier in Figure 13.c is particularly suited to this application. Unipolar-charged particles enter the classifier as an annular ring surrounding a core of clean air. A voltage with polarity opposite the polarity of the particles is applied to the central rod. The outer tube is electrically grounded. The charged particles are attracted toward the central rod with a radial velocity expressed in Equation (B.9). Particles with high mobility deposit near the top of the rod while lower mobility particles travel further down the rod before being deposited. If the geometry and electric field intensity are chosen properly, particles with mobility less than a given value (mobility cutoff) will not be deposited on the central rod, but will pass out the bottom of the classifier where aerosol sensors can detect the concentration. The mobility cutoff of a given geometrical design can be varied by changing the electric field intensity or the aerosol and clean air flow rates. Thus, in operation, one would measure the concentration at one mobility cutoff (corresponding to a predetermined particle size cutoff) and then at a different mobility cutoff (corresponding to a different particle size cutoff). The concentration of particles between the two sizes is the difference between the two concentration measurements.

Thus, an instrument based on this principle measures the number concentration within several size ranges. The size ranges are determined by the relationship shown in Equation (B.9). The velocity v from Equation (B.9) determines where the particle will land on the central rod.

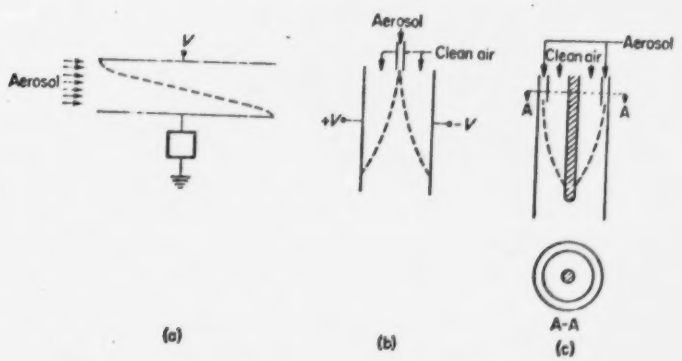


Figure 13. Aerosol mobility classifiers.[1211]

Two factors limit the particle size resolution of this type of classifier. The first is the difficulty in placing an equal number of charges on all particles of a given size. The second is the problem of introducing particles at the top of the mobility analyzer in a very thin annular ring so that all particles travel an equal radial distance through identical flow conditions to reach the central rod.

There are many ways to place an electrostatic charge on aerosol particles. Most of these are reviewed in Reference 1211 and will not be discussed here. The most successful for classifying 0.005 - 0.6 μm particles is shown in Figure 14 and is called a sonic jet unipolar charger. The details are discussed in Reference 68. The method of charging is called diffusion charging and is discussed in Reference 1211 and 56. The mobility of particles charged by this method allows good size classification from 0.01 - 0.2 μm. The classification below 0.01 μm deteriorates because only a very small fraction of such particles can be made to accept a single charge. Above 0.2 μm, the mobility versus particle size relationship slowly flattens until 2.0 μm particles have about the same mobility as 10.0 μm particles. The electrical charge n_p placed on equally-sized particles is quite narrow, resulting in relatively sharp size classification in the 0.01 - 0.2 μm range. For example, completely monodisperse particles (geometric standard deviation of 1.0) have a measured geometric standard deviation of 1.15 with an existing commercial instrument.[1344]

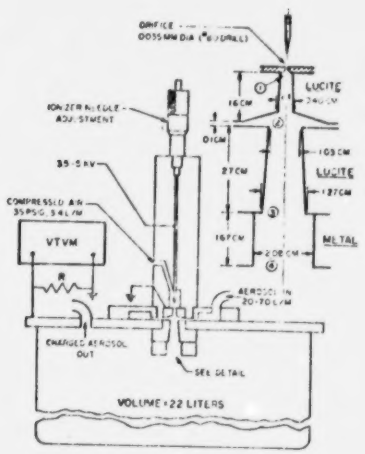


Figure 14. Sonic jet diffusion charger.[68]

Another charging technique, field charging, could probably be used to classify particles from 1.0 μm to 10 or 20 μm. However, this technique has not been developed as thoroughly and other classifying techniques appear more promising for the larger-sized particles.

The second factor limiting particle size resolution is the introduction of aerosol in as thin an annular ring as practically possible. This assures that all charged particles of equal mobility travel radially through identical conditions and their deposit is not spread out on the collection surface. The need for a reasonable through-put requires an annular ring of practical width. In practice, the ring width can be kept down to about 10% of the radial distance which the particle must travel.

This technique has been used to measure particle size in a number of studies of atmospheric and artifical aerosols.[27,40,42,61,68,1276,1285, 1344,1390]

An aerosol charge-mobility classifier instrument is manufactured by:

Thermo-Systems Inc.
2500 Cleveland Ave. N.
St. Paul, Minnesota 55113.

The instrument, the Whitby Aerosol Analyzer, can be used in several modes: (a) as an automatic concentration versus size detector, (b) as a size classifier, and (c) as a mobility classifier for an externally-charged aerosol. The present commercial model is large and would not lend itself readily to stack monitoring in its present form. The maximum aerosol temperature must be kept below about 100°F on the commercial unit because of contruction materials.

Electrostatic classification is a definite candidate for classifying 0.005 - 0.6 μm effluent particles. Recent improvements in the charger design and the mobility operating conditions make the size classification very good, especially in the 0.01 - 0.2 μm range.[1344] With proper design, the technique could probably be made to operate at either in-stack or out-of-stack conditions. Although this technique does not lend itself to stack applications in its present state of development and requires some development for such application, it remains the most practical classifying technique in its size range. Although considerable development could probably result in classification of particles above 1.0 μm, the availability of other techniques makes such development unimportant.

c. Sieve Classification

One of the best known methods of classifying powder particles into size fractions is sieving. This is usually done with a set of screens mounted in matched holders and stacked such that particles encounter progressively smaller openings as they fall through the screens. The particles which remain on each screen are then weighed to obtain the size distribution.

One of the greatest problems with sieves is getting all particles which should pass a given sieve to actually fall through and keeping those which should not from passing through. The method most often used to make particles fall through is to agitate the particles

violently enough to bounce each particle into many orientations and to break up loose agglomerates. However, the agitation must not be violent enough to break up the primary particles. These techniques have extended the lower size limit of sieving techniques down to about 10 μm diameter.

One such technique is acoustical agitation. An acoustical speaker, mounted either below or above the stack of screens, causes the particles to bounce violently. Such a unit is marketed commercially by:

Allen-Bradley Company
(street address unknown)
Milwaukee, Wisconsin

The lower size limit of the screens on this model is about 10 μm. The largest screen size available has about 600 μm holes.

A second method of agitating the particles is to periodically blast air upward through the screen. Such a unit is manufactured by:

Alpine American Corporation
3 Michigan Drive
Natick, Massachusetts 01762

The smallest advertised hole size of these screens is 15 μm. The largest is greater than 100 μm.

Another method of agitating particles on the screens is to wash the stack of screens in a liquid such as water during the sieving process. This helps achieve better classification, but care must be exercised to keep from losing or dissolving particles in the process.

One manufacturer of ordinary matched sieve sets is:

W. S. Tyler Company
(street address unknown)
Mentor, Ohio 44060

The holes in the sieves range from large sizes down to 44 μm.

An electromagnetic sieve shaker is manufactured by:

Geoscience Instruments Corporation
435 East 3rd Street
Mount Vernon, New York 10553.

Although sieving could be adapted to airborne particles, little application is expected for classifying stack effluents because it does not operate on small enough particles and the technique does not lend itself to automatic, continuous sensing of particle size. Some research application may be found in the manual sizing of large particles collected by effluent control devices. The agglomeration, deagglomeration, and fractionation of powder particles is a major problem as is screen binding.

d. Filtration

The efficiency of a filter as a function of particle size generally has a shape similar to Figure 15. If a particle distribution is located primarily above or below the minimum point, this feature can be theoretically used to size classify the aerosol. Filtration theory has been reviewed by many investigators, including References 1211 and 1333.

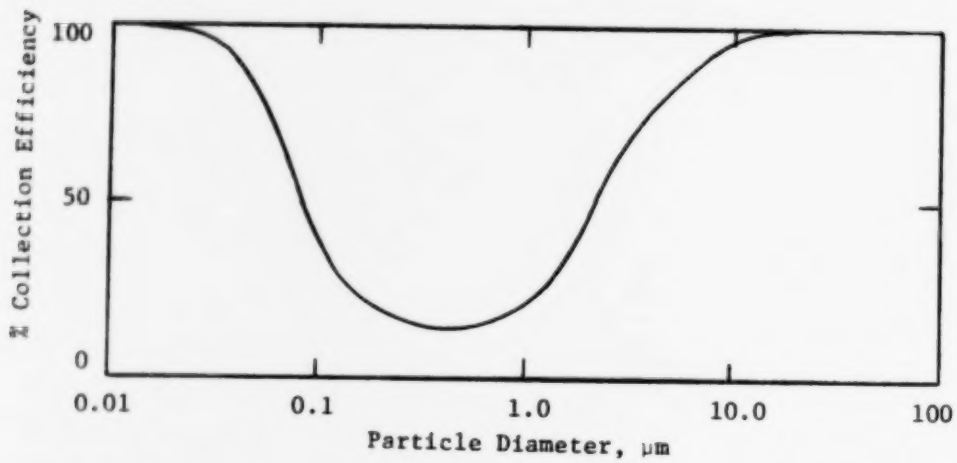


Figure 15. Typical filter efficiency curve. The exact location of the minimum shifts both horizontally and vertically with changes in filter media, face velocity, filter loading, and other factors.

If several filters are used, each with an efficiency curve falling in a different size range, the filters can be placed in series similar to a cascade impactor. The first filter will ideally collect everything above a given cutoff size (50% point on the efficiency curve). Each succeeding filter will collect a smaller size fraction.

An automated system may consist of cascaded filters with sensors removing a small part of the material passing through each filter. The sensor then measures the concentration of material below each filter's cutoff size.

This technique has several important problems. Filters become plugged, changing the efficiency curve and thus changing the size cutoff. The efficiency curve for most filters is not very steep, making the size cutoff rather poor. The practical range of this technique is from about 1.0 to 5 μm, a very narrow range. Size classification in the range below 0.1 microns has not proven practical. Since several other techniques appear to be considerably more promising within the same size ranges, filtration classification will probably not be used for stack effluents except for specific research applications.

e. Brownian Diffusion

For particles smaller than 1.0 μm, Brownian diffusion becomes an important factor governing the motion of an individual particle. Brownian motion of a particle is caused by the random bombardment of the particle by gas molecules. A single molecular impact does not change the direction and speed of an aerosol particle appreciably, but random collisions with a large number of molecules causes motion such as that shown in Figure 16.[1333] Fuchs[1333] and Davies[1211] discuss Brownian diffusion in considerable detail and much of the following discussion has been derived from them.

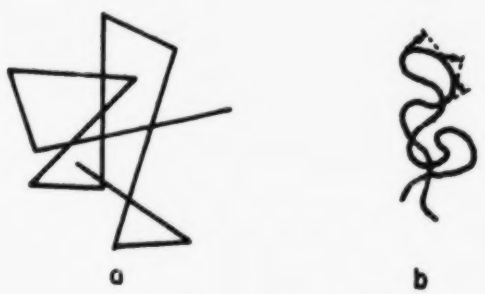


Figure 16. Trajectories of gas molecules (a) and particles undergoing Brownian motion (b).[1333]

The diffusion coefficient of a particle, a quantity characterizing the intensity of Brownian motion, can be expressed:

$$D = kTB \qquad (B.11)$$

where:

D = diffusion coefficient,

k = Boltzmann's constant,

T = absolute temperature,

$B = \frac{C}{3\pi\eta D_p}$ = particle mobility,

C = Cunningham's correction factor,

η = viscosity of the gas, and

D_p = particle diameter.

Table B.4[1211] lists diffusion coefficients at normal atmospheric conditions for particles from molecular size to 100 μm radius. Notice that the diffusion coefficient is much larger for small particles than for large ones.

As an aerosol flows through a tube, the Brownian motion of some particles will cause them to cross fluid streamlines and hit the tube wall. For particles in the size range where Brownian motion is important (below 0.1 μm), they will adhere strongly to the tube and not be reentrained. Thus, they are lost from the aerosol stream.

The rate of deposition of particles on the tube wall is a function of the particle size; the concentration of small particles decreases more rapidly than that of large particles. Considering only the deposition of particles caused by Brownian motion, the concentration of aerosol leaving a long, circular tube is[1211]:

$$\frac{\bar{C}}{C_o} = 0.819\exp(-14.63\Delta)+0.0976\ \exp(-89.22\Delta)+0.019\ \exp(-212\Delta) \qquad \text{(B.12)}$$

where:

$\bar{C}$ = average exit number concentration,

C_o = average inlet number concentration,

$\Delta = \frac{Dx}{d^2V}$,

x = length of tube,

d = tube diameter, and

V = average gas velocity.

Table B.4

The approximate molecular diffusion coefficients of small particles in air at 760 mm and 20°C.[1211]

Particle radius (μm)	Coefficient of diffusion, D (cm^2/sec)
10^{-4} (hydrogen molecule)	7×10^{-1}
5×10^{-4}	$5{\cdot}2 \times 10^{-2}$
10^{-3}	$1{\cdot}3 \times 10^{-2}$
5×10^{-3}	$5{\cdot}3 \times 10^{-4}$
10^{-2}	$1{\cdot}4 \times 10^{-4}$
2×10^{-2}	$3{\cdot}6 \times 10^{-5}$
5×10^{-2}	$6{\cdot}8 \times 10^{-6}$
10^{-1}	$2{\cdot}2 \times 10^{-6}$
2×10^{-1}	$8{\cdot}4 \times 10^{-7}$
5×10^{-1}	$2{\cdot}76 \times 10^{-7}$
1	$1{\cdot}3 \times 10^{-7}$
2	$6{\cdot}16 \times 10^{-8}$
5	$2{\cdot}4 \times 10^{-8}$
10	$1{\cdot}2 \times 10^{-8}$
20	$5{\cdot}9 \times 10^{-9}$
50	$2{\cdot}4 \times 10^{-9}$
100	$1{\cdot}2 \times 10^{-9}$

$\bar{C}/C_o$ is shown in Figure 17[1211] as a function of Δ. Equation (B.12) assumed (a) Re <2000 (laminar flow), (b) the tube is long enough so that end effects are negligible, (c) the velocity profile is parabolic, (d) the aerosol concentration is small enough so that particle interactions are negligible, and (e) other effects such as electrostatic forces do not affect Brownian motion.

Equation (B.12) shows that

$$\frac{\bar{C}}{C_o} = F(\Delta) \qquad \text{(B.13)}$$

where, using the relationship shown in Equation (B.11):

$$\Delta = \frac{Dx}{d^2V} = \left(\frac{kT}{3\pi\eta}\right)\left(\frac{C}{D_p}\right)\left(\frac{x}{d^2V}\right). \qquad \text{(B.14)}$$

The first term in Equation (B.14) is a function of the gas, the second term is a function of particle size, and the third term is related to the system geometry and flow rate. Thus, if a monodisperse aerosol passes through a given tube at known conditions, a measurement of $\bar{C}/C_o$ determines particle size.

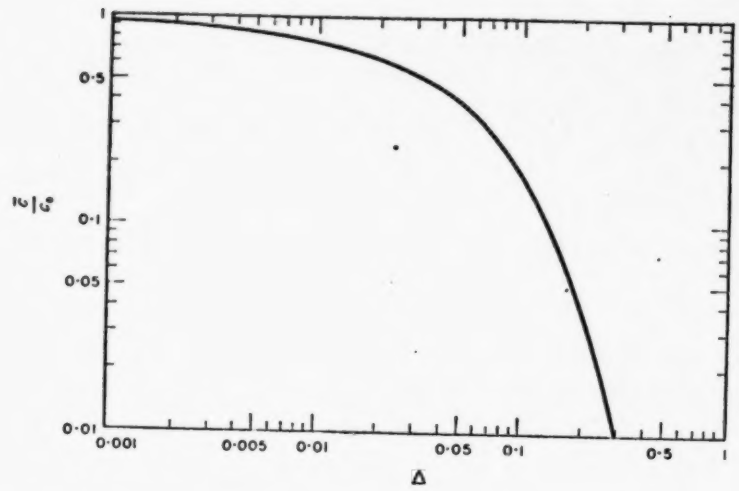


Figure 17. Diffusion to the absorbing wall of a long tube through which the flow is viscous an follows Poiseuille's Law.[1211]

For a polydisperse aerosol, several tubes can be used, each with different geometry and/or flow rates. Each tube has associated with it a certain particle size of which $\overline{C}/C_o = 0.50$. This particle size is called the cutoff size with most particles larger than this size passing through and most particles smaller being deposited. In this case, the fraction of the size distribution located between two given particle sizes is simply the difference between the fractions $\overline{C}/C_o$ measured at each condition.

The size range where this technique is useful is from 0.001 to 0.05 μm diameter. Above 0.05 μm, Brownian motion becomes insignificant compared to other motions. Below 0.001 μm is the molecular regime. The detector normally used for measuring $\overline{C}/C_o$ is a nuclei counter (see Volume I of this report). Since the size cutoff is not very sharp (see Figure 17), size measurements made in this way are not very accurate. However, this is the best known technique of size classifying 0.001 - 0.01 μm particles.

Husar[1390] suggests a somewhat different approach for using diffusion for sizing particles. It also describes a very recent design of a sizing instrument and measurements made by the instrument. Tables of design criteria will prove useful for the design of other such instruments.

Several problems limit the use of diffusion techniques for classifying effluent particles. Large particles above about 1.0 μm should be eliminated before the smaller particles pass through the diffusion tubes. If the temperature of the aerosol stream and the tubes are not in equilibrium, thermal forces and condensation may confuse the deposition. Other deposition mechanisms may also confuse the deposit, including gravity and even low levels of turbulence.

The diffusion technique may see application to stacks only for classifying 0.001 - 0.01 μm particles. This will probably be only in research application, although this technique is the only known size classification method in the 0.001 - 0.005 μm range.

f. Other Forces

Many other forces can act on small particles. Some of these include thermophoresis, diffusiophoresis, photophoresis (a form of radiometric force), and magnetic forces (see, for example, Reference 1333 and 1211). Although any or all of these forces may have an important effect on the motion of an aerosol particle in a given system, no way is known to classify particles by size using these phenomena in practical situations.

2. Particle Sensing Techniques

Volume I and II of this report discuss all known techniques for the sensing of aerosol concentrations in practical situations. Although Volumes I and II are oriented toward measurement of the mass of aerosol particles, all other comments are appropriate for the present application. The reader is referred to Volume I for a brief, but comprehensive, survey of all sensing techniques; and to Volume II for detailed discussions of the viable techniques for effluent particle sensing.

3. Combinations of Classifiers and Sensors

Many factors must enter into the choice of a size classifier-concentration sensor combination for any particle sizing application. A number of these factors have been discussed in the introduction of this volume. After studying his application carefully, the investigator must decide what particle size range is of primary interest, what type of size classification he prefers, and which parameter of the particles he wishes to sense. The remainder of this section presents those classifier-sensor systems which appear most practical for automatic or semi-automatic measurement of the concentration of particles within specified particle size ranges in effluent streams.

Nearly any size classifier can be used with nearly any concentration sensor to measure the size distribution of aerosols. It can be seen from the list of particle size classifiers (at least 10 separate methods) and the longer list of particle concentration sensors (at least 31 separate methods) that several hundred possible combinations exist. Not all of these combinations are technically feasible and most of them are not practical for effluent particle sizing. Table B.5 lists 27 combinations which appear to be technically feasible and which also appear to be the most practical for application to effluents. Not all of the combinations in Table B.5 are equally applicable, however, and most combinations have not yet been developed. The remainder of this discussion will point out strengths and weaknesses of the most promising of these combinations.

None of the combinations in Table B.5 covers the entire range of particle sizes found in effluent ducts (from about 0.001 μm up to at least 100 μm diameter). Thus, one must choose a smaller particle size range of primary interest, choose a system which covers that range, and determine the limitations of the chosen system.

Table B.5. The operable size ranges of practical combinations of size classifiers and sensors. All numbers are the diameter, in microns, of a spherical particle with a density of 1.0 gram/cubic centimeter.

PARTICLE SIZE CLASSIFIER		CONCENTRATION SENSING TECHNIQUE						
		MASS		OPTICAL				
		BETA RADIATION ATTENUATION 0.01 – 100	PIEZOELECTRIC QUARTZ CRYSTAL 0.01 – 20	LIGHT TRANSMISSION 0.2 – 100	PHOTOMETRY 0.2 –50	SOILING POTENTIAL 0.2 – 50	ELECTROSTATIC ION CAPTURE AND ATTENUATION 0.005–100	NUCLEI COUNTER 0.001 – 0.05
AERODYNAMIC	IMPACTOR 0.2**- 30	0.2*- 30	0.2*- 20	0.2 — 30	0.2 — 30	0.2 — 30	0.2 — 30	–
AERODYNAMIC	CYCLONE 0.5 - 30	0.5*- 30	0.5*- 20	0.5 — 30	0.5 — 30	0.5 — 30	0.5 — 30	–
AERODYNAMIC	GRAVITATIONAL ELUTRIATOR 1.0 - 100	1.0*- 100	1.0*- 20	1.0 – 100	1.0 — 50	1.0 — 50	1.0 — 100	–
AERODYNAMIC	GRAVITATIONAL SEDIMENTATION 1.0 - 50	1.0*- 50	1.0*- 20	1.0 — 50	1.0 — 50	1.0 — 50	1.0 — 50	–
	ELECTROSTATIC 0.005 - 0.6	–	–	–	–	–	0.005 — 0.6	0.005 — 0.05
	BROWNIAN DIFFUSION 0.001 - 0.05	–	–	–	–	–	–	0.001 — 0.05

*Although this is the lowest size cutoff of the classifier, the sensor can detect smaller particles below this size cutoff, lumping them into one size range.

**Low pressure impactor may prove useful down to 0.05 microns for some applications where volatile particles are not present.

The only combination which can measure size distributions down to 0.001 μm is the Brownian diffusion classifier and nuclei counter sensor as shown in Figure 18. Such a system has been used on artifical laboratory aerosols with some degree of success in several research laboratories. The system consists of a set of diffusion tubes of different lengths (called a diffusion battery) and a condensation nuclei counter to sense the aerosol concentration entering and leaving each tube. Each tube removes particles smaller than a given size, called the cutoff size. Each tube has a different cutoff size. Thus, the concentration of particles within the size range between two specific tube cutoff sizes is the difference between the two exit nuclei counter concentrations. The sharpness of the size classification is not very good, but this is the only potentially-automatic measurement method which operates in this size range.

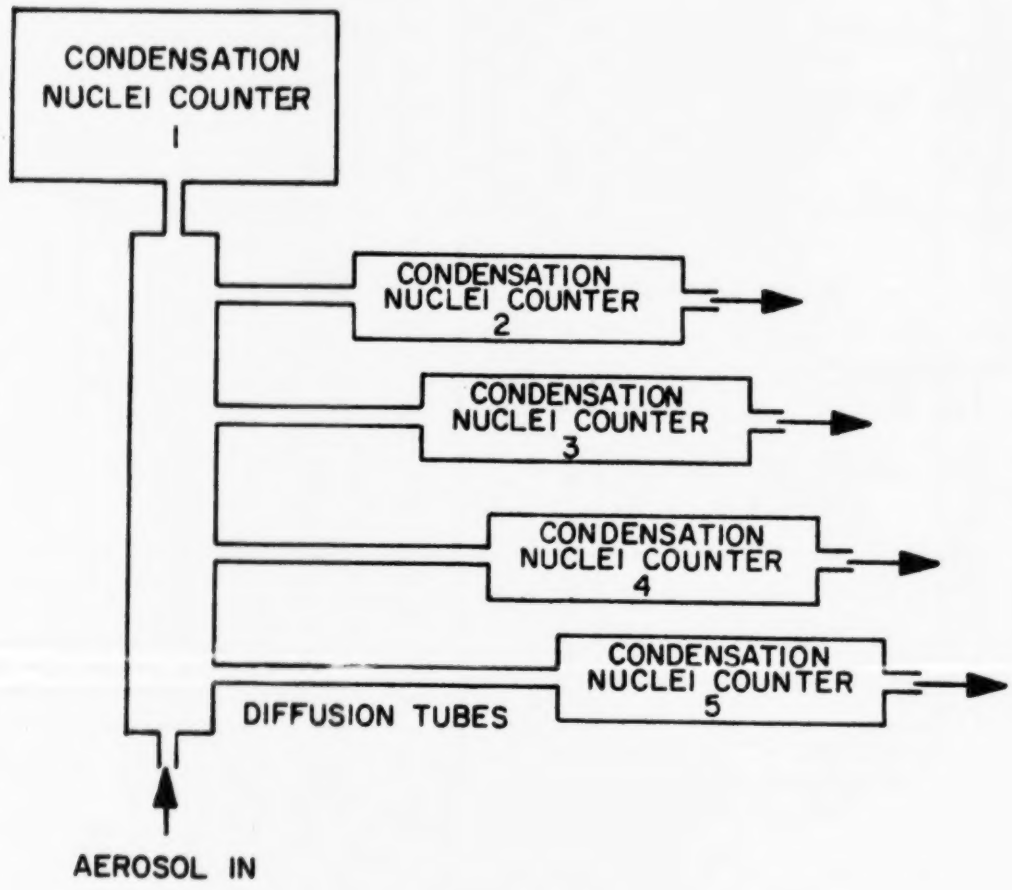


Figure 18. Diffusion battery classifier with nuclei counter concentration sensors. This technique could probably operate in the 0.001 - 0.01 μm size range. Condensation nuclei counter 1 measures the concentration before aerosol passes through diffusion tubes to the other condensation nuclei counters.

The only alternative method (not automatic) is electron microscopy which can be performed only on non-volatile solid particles (not liquid). Electron microscopy in the size range below 0.01 μm is very difficult, if possible at all.

In using the diffusion battery, all particles greater than about 0.1 or 0.2 μm should first be eliminated, e.g., by impaction. This reduces any interference caused by the large particles. Although this technique has been used in laboratory research studies, much development remains to make it useable for effluent particles.

At present, the optimum choice for classification in the size range between diffusion batteries and aerodynamic methods is electrostatic classification. This system consists of an electrostatic charger, an electrical mobility classifier, and either a charge collector (e.g., a particle filter) or a condensation nuclei counter to measure aerosol concentration downstream of the mobility classifier (see Figure 19). As the mobility classifier is adjusted to collect particles with various mobilities, the aerosol concentration is noted at each mobility. The concentration within a given size range is equal to the difference in concentrations measured with corresponding mobility cutoff settings. In the case of the charge collector sensor, the current draining off the collected particles is measured by an electrometer. By knowing how many charges have bled off each particle, one can calculate the aerosol concentration which was responsible for the measured current flow. A commercial system designed for operation in atmospheric aerosol has a high enough resolution in the 0.01 - 0.3 μm range to measure a geometric standard deviation of about 1.15 when sampling a completely monodisperse aerosol with a geometric standard deviation of 1.0. The instrument has somewhat lower resolution over the complete 0.005 - 0.6 μm range. The electrostatic sensor has proven superior to the condensation nuclei counter in atmsopheric aerosols. Although considerable development and testing is necessary to apply this technique to effluent streams, no basic problems are foreseen.

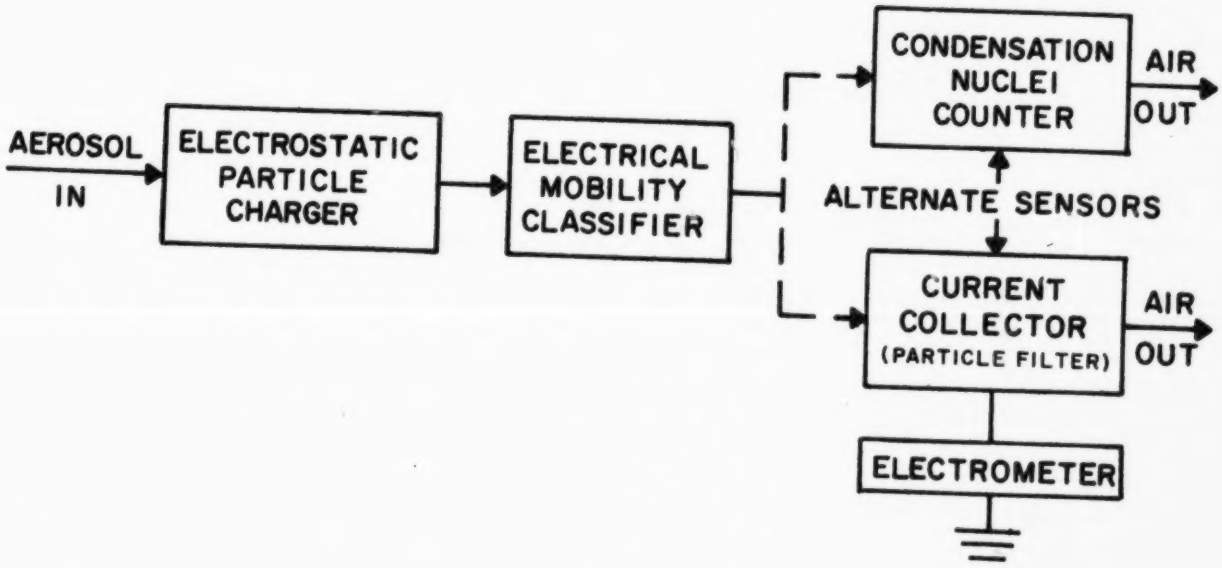


Figure 19. Electrostatic classifier with two alternate particle sensors: (a) electrostatic sensor, and (b) condensation nuclei counter sensor. This technique operates in the 0.005 - 0.6 μm size range.

There are several choices of classifier-sensor combinations for the 0.2 - 100 μm range. All of the aerodynamic classifier systems can be arranged with the classifier upstream and in series with the sensor, as shown in Figure 20.

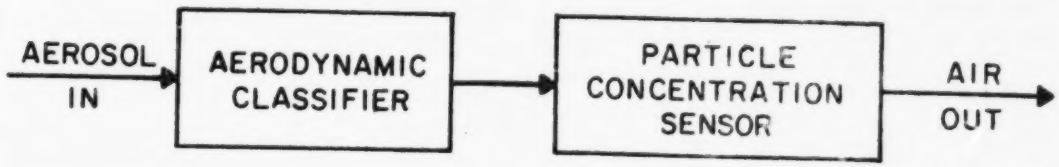


Figure 20. One possible arrangement of classifier and sensor for all aerodynamic classification systems listed in Table B.5.

In this case, the sensor detects everything passing through the classifier, i.e., the particles smaller than the designed cutoff. To measure several size fractions, one must use several classifier operating conditions, or, more commonly, several classifiers, each designed for a different size cutoff, with corresponding particle sensors. In the case of the mass sensors, the concentration of particles passing the last classifier stage can be lumped into one size fraction.

A look at several specific design concepts will make clear how other combinations can be assembled. First, we will look at the impactor-sensor combination. One system could be arranged as shown in Figure 21. In this design a continuous flow of aerosol is drawn into the cascade impactor. Sensor #1 measures the total concentration of the aerosol stream by sampling a small fraction of the impactor flow. The aerosol entering the impactor passes through impactor Jet #1 which collects particles greater than size $D_{p,1}$. Sensor #2 measures the remaining concentration (particles smaller than $D_{p,1}$). The aerosol then passes through impactor Jet #2 where particles larger than $D_{p,2}$ (and $<D_{p,1}$) are collected. Sensor #3 measures the remaining concentration, etc. The last sensor #5 measures the aerosol concentration passing the last impactor (#4). As many stages can be added as desired. However, as more stages are added, the difference between consecutive measured concentrations decreases, making the measurement within each size increment less accurate. This system, with any of the sensors listed in Table B.5, could be assembled with very little modification from present commercially-available equipment. The sensors with fastest response are probably the photometer[124] and the piezoelectric sensor. Light transmission is just as fast as photometry, but no commercial unit small enough for this application is available, and photometry is more sensitive. The beta radiation attenuation and soiling potential sensors could be applied, but currently available models are not as sensitive as either photometers or piezoelectric sensors. Electrostatic sensors require development.

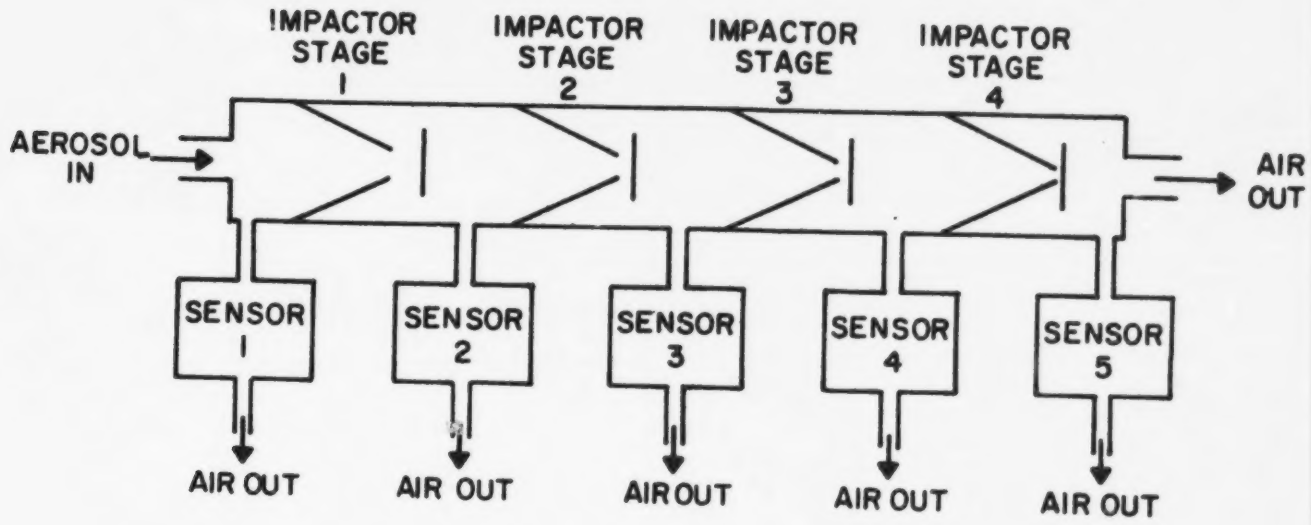


Figure 21. An impactor-sensor particle size measuring system using an aerosol concentration sensor behind every impaction stage. Each sensor measures the concentration of particles smaller than the preceding impactor cutoff size.

A second impactor design, using the impactor-piezoelectric sensor as an example, is shown in Figure 22. In this design, all of the aerosol passes through every impactor jet. The impaction deposition plates are piezoelectric quartz crystals driven by external oscillators. In this case, each crystal senses the size fraction larger than the size cutoff of its corresponding jet and smaller than the size cutoff of the preceding impactor stage. A piezoelectric concentration sensor using electrostatic precipitation can sample the aerosol passing the last impactor stage. The same arrangement could be used with beta radiation attenuation and soiling potential. However, neither is as sensitive as the piezoelectric technique.

A third practical impactor design uses the void-space impactor concept as shown in Figure 23. As particles impact into the void (air) space, a sample of the void air is drawn through a sensor. The sample flow of void air must be much smaller than the air flow through the impactor jet. This technique avoids the problem of particle blowoff which occurs as the impacted sample builds up on conventional impaction plates. Nearly any sensor can be used with the void impactor. A unique feature of this technique is the concentrating effect of the system. After

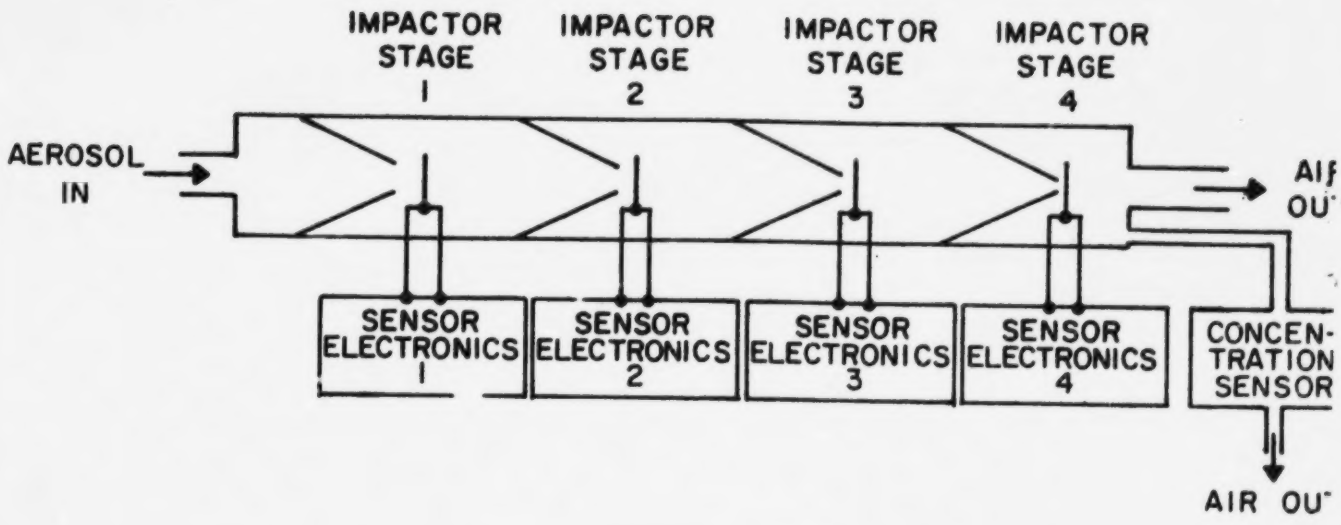


Figure 22. Another impactor-sensor particle size measuring system using an impaction plate which actively senses deposited particles. This example shows piezoelectric crystal sensors. Beta radiation attenuation or soiling potential could also be applied with this design.

the system reaches steady-state operation, the aerosol in the void sample flow becomes concentrated:

$$C_{vs} = C_o \frac{Q_j}{Q_{vs}} \qquad (B.15)$$

where:

C_{vs} = concentration of void sample flow,

C_o = initial concentration of the identical aerosol size fraction,

Q_j = flow rate through the impactor jet, and

Q_{vs} = flow rate of the void sample to the sensor.

The concentrating effect can make some of the less sensitive sensors applicable. The void-space impaction system responds more slowly to fluctuations in aerosol concentration than the design shown in Figure 21 and 22 because of the damping effect of the void space. Hardware of this type employing beta radiation attenuation sensing is being fabricated by Environmental Research Corp., St. Paul, under contract to Environmental Protection Agency/NERC.

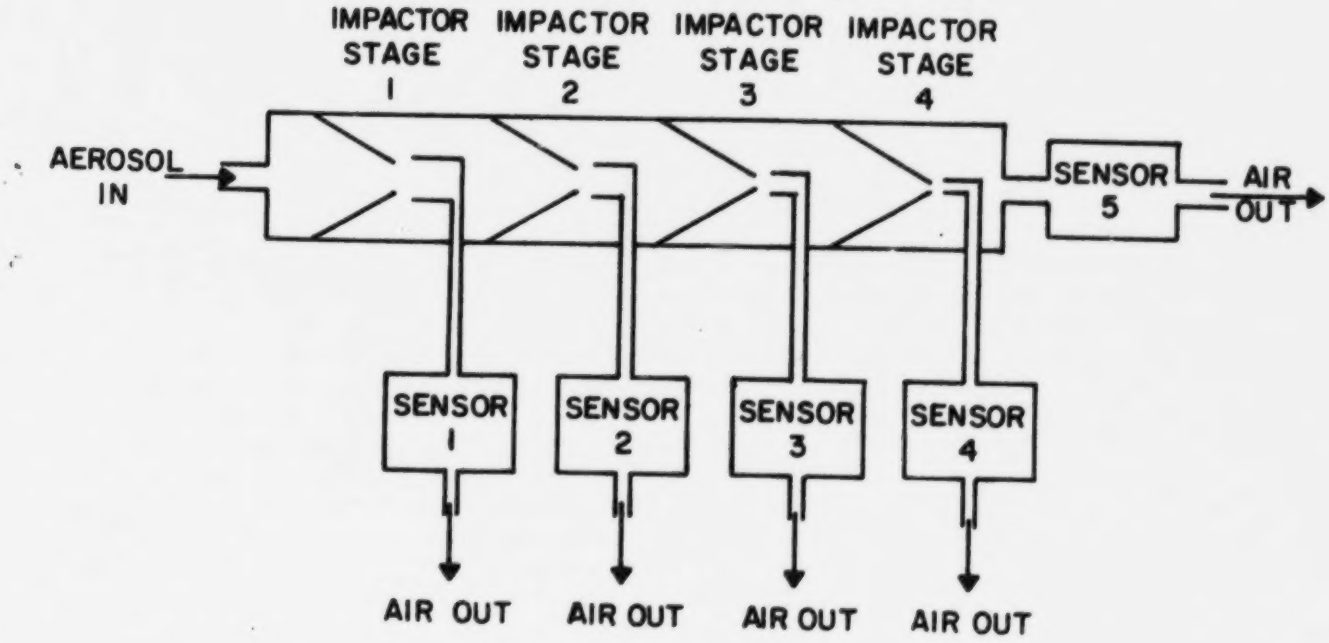


Figure 23. An impactor-sensor particle size measuring system using an aerosol concentration sensor to measure the concentration of particles impacted into a void space. The air flow rate passing out of each void space must be very small compared with the air flow through each impactor stage.

The cyclone classifier is particularly useful as a single-stage size classifier in the 0.5 - 20 μm size range. It has been used in industrial hygiene sampling applications as a simulator of particle retention in the upper respiratory system in humans. Thus, anything passing through the appropriate cyclone (small size fraction) is defined as respirable dust. The cyclone classifier with appropriate particle concentration sensors will probably find a similar use in stack effluent monitoring. The size classification with a cyclone is not as sharp as with an impactor, so detailed size analysis with several size stages would preferably be done with impaction. However, the cyclone has several advantages for single-stage classification of effluent particles:

1. Can operate continuously for an indefinite time without any deterioration in classification ability and without phenomena such as particle bounce and particle blowoff which hinder continuous operation of all impactors except void impactors,

2. Recognized as the standard simulator of the respiratory system for industrial hygiene applications, and

3. Simulates the operation of cyclone effluent control devices, making cyclone classifiers especially useful in evaluating such control devices.

A cyclone classifier with appropriate sensors is shown schematically in Figure 24. The sensor which measures the concentration of small particles passing through the cyclone can be nearly any sensor listed on Table B.5. Probably photometry and piezoelectric quartz crystal sensors would be most useful because of their high sensitivity. The elimination of the large particles would probably eliminate any particle adhesion problems normally encountered with the piezoelectric sensor. However, the sensor which measures the large particles coming out from the cyclone must sense large, powder-like particles. The beta radiation attenuation and soiling potential sensors, both with filter-tape particle collectors, would probably be superior to other sensing techniques for this measurement.

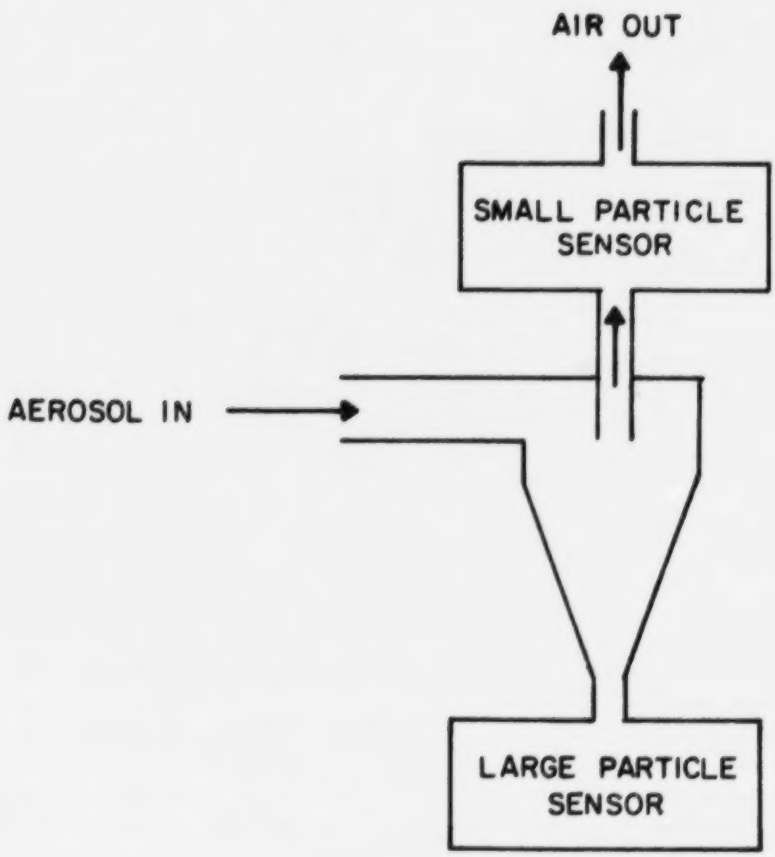


Figure 24. Single-stage cyclone classifier with two concentration sensors: one for the small particle fraction and one for the large particle fraction.

Gravitational sedimentation has been used, particularly in England, to simulate the deposition in the human respiratory system. This principle could be used to separate large particles from an effluent stream as does the cyclone. However, there does not seem to be a simple way to sense the coarse particle fraction separately. One could sense the total concentration and the fine fraction, and then subtract to obtain the coarse-particle fraction, but this is not as accurate as sensing the coarse and fine fractions separately as with the cyclone classifier.

Gravitational elutriation could be used in much the same way as cyclone classification. Classification into two size fractions is relatively simple, but the size cutoff is probably not sharp. Both the fine and coarse fractions could be sensed directly as with the cyclone. Although this technique offers promise as a single-stage classifier, it has not been developed for aerosols such as stack effluents. Thus, development and testing is needed to more fully evaluate its characteristics for this application.

C. TECHNIQUES WITH INSEPARABLE CLASSIFICATION AND SENSING

On several aerosol size measuring techniques, the apparatus used to classify the particles into various size ranges cannot be physically separated from the apparatus used to sense the particle concentration within each size range. In these cases the processes of classification and sensing occur simultaneously. Most of these techniques involve the interaction of the particles with electromagnetic radiation and are discussed in considerable detail in Volume II of this report. The discussions below summarize each technique and describe briefly how each could be adapted to measurements of particle size in effluent streams. The techniques include:

1. Optical Techniques
   a. Optical Particle Counters
   b. Angular Light Scattering
   c. Multi-Wavelength Light Transmission
   d. Light Scattering: Polarization Ratio Method
   e. Holography
   f. Automated Microscopic Method

2. Impact and Momentum Sensors

3. Piezoelectric Single Particle Counter

1. Optical Techniques (See Hodkinson[1211], pp. 316-317, Table III, on various ways to use light scattering to measure particles)

   a. Optical Particle Counters

   The scattering of light by individual particles as they pass, single-file, through a beam of light has been used extensively to measure the size distribution of airborne particles. The principle of operation can be seen in Figure 24. Aerosol is drawn through the sampling tube by suction. As a particle passes through the sensing volume, it scatters a pulse of light which is detected by the photomultiplier tube. The output of the photomultiplier tube is a series of voltage pulses, one for each particle passing through the sensing volume. The amplitude of the voltage pulse is proportional to the size of the particle. By classifying the amplitudes of the voltage pulses by means of a pulse-height analyzer, the size distribution of the aerosol can be measured.

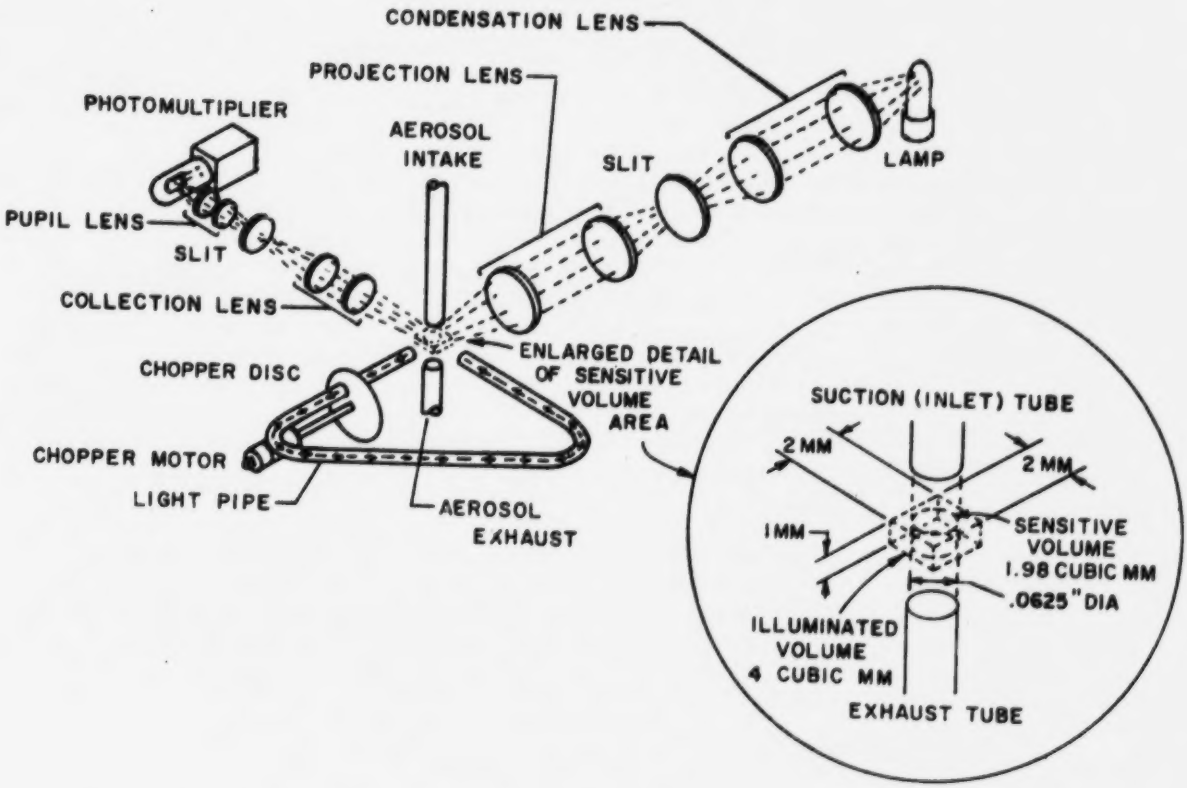


Figure 25. Principle of operation of an optical particle counter which senses light scattered at 90° from the incident beam. (From a Royco Instruments, Inc. instruction manual)

Many particle characteristics, in addition to size, affect the amplitude of the scattered light, including the refractive index, the shape, and the surface optical properties of the particle, the angle between the incident light and the scattered light, the orientation of a non-ideal particle in the light beam, and the wavelength characteristics of the light source-photomultipler system. With any given instrument design applied to a specific aerosol, most of these extraneous effects can be minimized with appropriate calibration. An aerosol with different optical properties requires a new calibration. If all of these secondary effects are ignored, an optical counter measures the number concentration within size ranges classified by particle surface area.

The design of the optics of an optical particle counter, including the choice of scattering angle and the use of lasers instead of a multi-wavelength light source, is quite controversial. Several commercially-available designs detect forward-scattered light, i.e., light scattered in the same direction as the light beam travels. This design usually minimizes the effect of particle refractive index.[143] With proper design and calibration of a multi-wavelength system, the use of laser light sources does not appear to offer significant advantages for most applications.

The concentration of particles sensed by an optical particle counter must be low enough so that the chance of more than one particle occupying the sensing volume at one time (physical coincidence) is small. If more than one particle is present in the sensing volume the scattered light detected by the photomultiplier will be the sum of the light scattered by both particles. Thus, the instrument will detect only one particle, measuring it somewhat larger than either of the actual particles. For application in effluent streams, dilution of the sample with clean air is necessary to reduce coincidence errors to an acceptable level. Dilution by 1,000 to 10,000 times would be required with present commercially-available counters. If the size of the viewing volume can be significantly reduced, less dilution will be required.

A problem analogous to physical coincidence is electronic coincidence. Electronic coincidence occurs when the electrical signal from a second particle arrives before the system has had sufficient time to process the signal from the first particle. Possible solutions to this problem are 1) improvement in the speed of the electronics, 2) dilution, and 3) reduction in the size of the viewing volume.

The theoretical lower limit of particle size which can be detected is determined by the scattering of light by the gas in the sensing volume. For practically-sized sensing volumes, this limit is approximately 0.1 - 0.2 μm diameter for carefully-controlled laboratory aerosols.[1388] Most commercially available optical counters operate down to 0.3 μm which is nearly the optimum. If larger numbers of 0.1 μm particles are present in the aerosol, the counter may count fluctuations in the concentration of these particles as if they were particles in the range above 0.3 μm.[680] This could also limit the lower detectable size of an optical counter.

The upper size limit of the optical counter is determined by the fluid mechanics problem of getting the airborne particles into the sensing volume. Low flow rates and concentration are needed to reduce the size of the viewing volume which in turn reduces coincidence losses and increases the sensitivity of the sensor to small particles. With these low flow rates, large particles (above 5 or 10 μm) tend to settle out of the sampling tube before reaching the sensing volume. A carefully designed

inlet flow system can greatly improve the chance of sensing large particles, but about 30 μm appears to be the practical limit with present commercial instruments with carefully modified inlets. There is no theoretical upper size limitation of the light scattering phenomena itself.

Despite these important limitations, optical particle counters will undoubtedly find use in research measurements of particle size distributions in effluent streams. The optical counter will not cover the entire size range of effluent particles, as is true of any sizing technique, but it does cover an important size range. It appears that the technique will not be used for routine monitoring of effluents because of the difficulties in bringing a representative sample to the sensing volume. When used with other instruments so that a wide size distribution is measured, the optical particle counter can be a powerful tool for understanding the dynamics of any aerosol system.

The optical particle counter is covered in greater detail in Volumes I and II of this report. A complete list of references is included in Volumes I and II. Many good reviews of light scattering phenomena are available, including those by Hodkinson,[1211] Hodkinson & Greenfield,[143] Kerker,[1215] and Van de Hulst.[1201] Technical descriptions of commercially available instruments are authored by Zinky,[370] Ogle,[580] Randall & Keller,[1210] Martens & Keller,[756] Martens & Fuss,[670] Martens,[578] and Sinclair.[615] Other special purpose models are described by Thomas, et al,[120] Moroz, et al,[1128] Whitfield and Mashburn,[949] Neitzle,[824] Nelson,[276] Mumma,[598] Gebhart, et al,[1388] and Kiktenko, et al.[1066] Most of these references discuss instruments designed for clean room monitoring. Several discuss atmospheric air pollution measurements.

b. Angular Light Scattering

Angular light scattering refers to the scattering of light by an aerosol particle at various angles with respect to the incident light beam. To measure the angular distribution of scattered light, the observer or light detector must measure the relative intensity of light in each direction around a particle. The shape of the angular scattering distribution changes as particle size varies. Thus, the shape of the angular distribution of scattered light is a measure of particle size.

This technique is discussed in detail in Volumes I and II of this report, by Kerker, et al,[70] and by Kratohvil & Smart.[842] Discussions of the general principles of light scattering also cover the angular distribution of scattered light.

An instrument utilizing angular scattering for analysis of single aerosol particles has recently been developed by:

Science Spectrum, Inc.
1216 State Street
P.O. Box 3003
Santa Barbara, California 93105

This technique has been used only in research laboratory applications. Considerably more theoretical and experimental work remains to demonstrate the utility of this technique. The procedure is now primarily manual with no simple method of automation available. The data reduction technique is also manual. For these reasons, this technique currently is probably unsuited for particle size distribution measurements of effluent streams.

c. Multi-Wavelength Light Transmission

The extinction of a light beam as it passes through a cloud of aerosol particles will change if the wavelength of the light beam changes. The type and amount of change depends on the size of the aerosol particles. This dependence, a rather complicated one, is discussed in detail in Volume II of this report and by Kerker[1215] and will not be repeated here. Measurement of the transmission of light at several wavelengths through an aerosol cloud can result in an estimate of the mean volume-surface particle diameter in the range of size from about 0.2 - 2 μm diameter. The estimate is not very accurate unless the size distribution is narrow. Effluent particle size distributions are nearly always quite broad. However, the measurement is very simple and inexpensive to make, requiring only a simple transmissometer with variable wavelength. The wavelength variation can be performed by a disk made up of several different filters. Several methods of data reduction are described in Volume II.

Although this technique cannot measure the complete size distribution, it can measure the volume-surface diameter with reasonable accuracy in the 0.2 - 2 μm range. Its simplicity as applied to effluent streams make further investigation desirable. If some way can be found to automate the data reduction, probably by a computer technique, the technique could result in useful particle size information at low cost and complexity.

d. Light Scattering: Polarization Ratio Method

When unpolarized incident light is scattered by a particle, the scattered light intensity can be described by two plane polarized components: i_1 perpendicular, and i_2 parallel to the plane of observa-

tion. There is a relationship between the intensity of scattered light and the wavelength of incident light, the particle size, shape, size distribution, index of refraction, and observation angle. In the polarization ratio method, the ratio i_1/i_2 is a measure of the particle size.

This technique, described in detail in Volume II, is practical only for measuring size distributions with a standard deviation of less than 0.3. Effluent particles have a much wider spread of particle sizes, making this technique impractical.

e. Holography

Holography is a technique by which three-dimensional information is recorded on a two-dimensional photograph. The technique consists of photographing the interference pattern that exists when a diffracted or object field (Fresnel or Fraunhofer diffraction pattern of the object) is allowed to interfer with a reference field or background wave. The image can be later reconstructed and any part of the three-dimensional reconstructed image can be focused or analyzed by simply placing the focusing plane or analyzer in the reconstructed image. The photographed object, e.g., a cloud of aerosol, is not disturbed in any way. The hologram is a permanent, three-dimensional, photographic record of the cloud.

Holograph is presently being used successfully by TRW Systems Group under an EPA contract to study the spatial distribution of clouds of particles within a coal-fired, steam-generating combustion chamber.1257,1279 The limit of resolution of this system (a lensless system) is about 25 μm and is determined by the photographic film quality. The depth of field of the system is over 30 feet. A high-quality telescope could increase the resolution to about 1 μm, but the depth of field would then be only millimeters. For measuring the size distribution of particles in effluent streams, a resolution of at least 1 μm would be necessary. The lack of depth of field would be severely restrictive.

The analysis of a reconstructed hologram of aerosol particles can be automated by scanning the entire reconstructed image in three-dimensions. The scanner could be a light-intensity sensor (photomultiplier) which could have a data analysis system nearly identical to that used in optical particle counters. The result would then be the number concentration of particles in given size ranges. This size distribution could be measured within various portions of the reconstructed image yielding the spatial distribution of the particle size distribution. Although such a system does not exist, it appears that nearly all components of such a system have been developed for other uses. Although present holographic technology is limited for continuous monitoring applications by its resolution and depth of field, such a system would be a very useful tool in many research studies.

Holography is a complex science in an infant state of development. A chapter in Volume II discusses holography in more detail. Developments currently being made will undoubtedly make large improvements in the applicability of holography to the measurement of individual effluent particles.

f. Automated Microscopic Method

Microscopic methods of particle sizing have undergone considerable automation in recent years. It is now possible to automatically perform nearly all of the tedious counting and sizing process. One present method requires the human operator to obtain a representative sample which is compatible with the microscope. The operator places the sample in the microscope and focuses on the desired portion of the sample. The image is then relayed to a TV screen where a computerized electron beam scans the image. The scanner detects the size of each object on the screen by sensing dark and light spots. The computer then categorizes the detected spots by size and prints out a particle size distribution. The operator must choose other fields of view of the sample and other magnifications. Electron microscope analysis can be performed in a similar way.

It appears possible to automate the entire sizing system for a given application. Nearly all parts of such a system have been developed before for other applications. The prime obstacle appears to be the rather extreme mechanical and electronic complexity of such a system. The system would consist of an automated sampling system which would obtain representative deposits of effluent particles on a suitable surface and pass these sample deposits on to the microscopic system. The automated microscopic system would then choose a suitable field of view, focus on the field of view, perform its counting and sizing procedure, and print out the results. The system would have to perform analysis at several different magnifications to assure accurate statistical analysis of all reasonable size ranges. The design of such a system would appear to be a matter of connecting appropriate components and programming a computer as a process controller and data analyzer. However, the cost would be very high and the complexity would undoubtedly lead to poor reliability.

The problem areas of such a system include the resolution limits and automatic focusing complexities, the statistical limitations of any microscopic study which requires examination of adequate numbers of individual particles and several magnifications to cover the wide particle size range of effluent particles, the complexity of the entire system, and the prohibitive cost of the system. These restrictions probably limit such a system to research programs and prohibit application for routine continuous measurements.

2. Impact and Momentum Sensors

When a moving particle strikes a surface, its momentum is transferred to the surface. If the surface is suspended in such a way that it can vibrate, the amplitude of vibration is proportional to the transferred momentum. This principle has been used to detect the momentum of micrometeoroids striking spacecraft.[252] In most applications, a piezoelectric transducer is used to convert the mechanical vibration into an electrical signal.

One of the most sensitive momentum transducers is shown in Figure 26. When a moving particle strikes the target, the piezoeletric beams deflect resulting in a damped oscillating electrical signal. The amplitude of the oscillation is calibrated in terms of particle momentum. Thus, if the velocity and density of the particle is known, the particle size can be calculated. The piezoelectric beams used in this design[252] are polycrystalline-modified lead zirconate titanate ceramic. This material is described as being a nearly ideal sensing element.[252] The threshold sensitivity of the momentum transducer is about 10^{-5} dyne-sec.

In an analytical evaluation of this instrument for use as a particle size transducer for aerosol particles, it was found that particles below 30 microns could not be accurately sized assuming the ultimate momentum resolution (10^{-5} dyne-sec.), reasonable particle velocities (10^4 cm/sec.), and unit density particles.[2] It appears to be difficult to accelerate the particles to higher velocities without introducing aerodynamic instability into the sensor. Perhaps the aerosol beam technique[1273,1361,1362] could be used for this purpose. However, the inability of this sensor to detect particles below 30 microns makes it relatively useless for effluent aerosols.

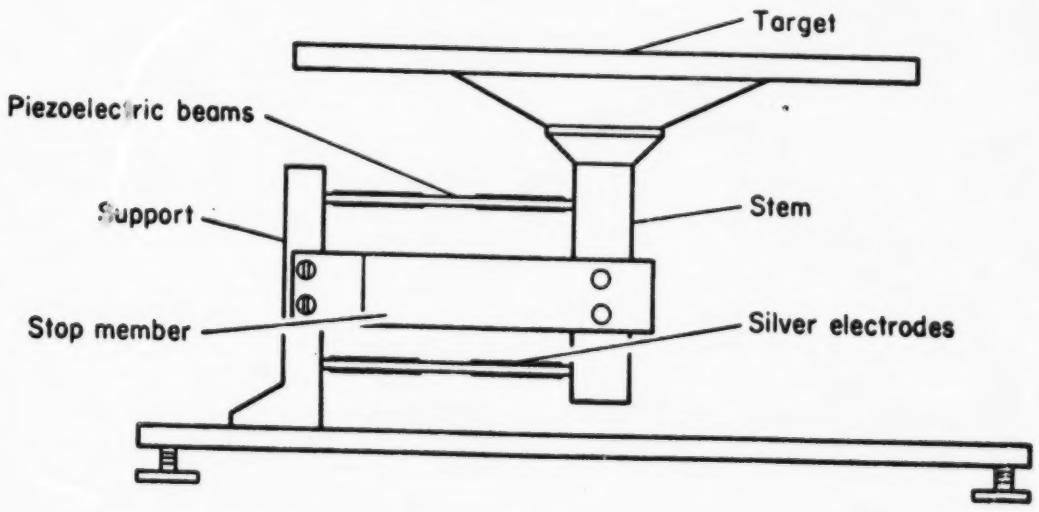


Figure 26. Schematic of a particle momentum sensor which uses piezoelectric beams as the transducer.[252] Particles strike the target, causing it to vibrate which, in turn, causes an electrical signal in the piezoelectric electronic circuit.

3. Piezoelectric Single Particle Counter

A piezoelectric microbalance can sense the addition of a single particle to its surface.[1223] Rather than measuring frequency shifts caused by a number of particles added to the crystal surface as done the standard piezoelectric microbalance (see Volume II of this report), the single particle counter differentiates the frequency signal resulting in a pulse whenever a single particle becomes attached to the crystal surface. The magnitude of the pulse is related to the mass of the particle. Thus, if particle density is known, the size can be calculated. A pulse-height analyzer can be used to classify the pulses into particle size range.

The ultimate size resolution claimed for this technique is about one micron for unit density spheres.[1223] The particle must adhere solidly to the crystal surface immediately upon contact, or the pulse magnitude will not be proportional to particle mass. The concentration and sampling rate must be low enough to prevent more than one particle from striking the crystal at one time. It appears that no more than about 10^3 particles per second can be sampled. The crystal sensor is somewhat sensitive to temperature, relative humidity, condensible vapors, and any other foreign material which can adhere to the crystal surface.

One can also measure the mass concentration with the piezoelectric single particle counter by monitoring the rate of change of frequency during the time period of interest. Thus, it can also be used as a mass concentration monitor as described in Volumes I and II of this report.

This technique has just recently been introduced to aerosol science and is not yet very developed. Thus, it is not clear which or how many of the potential problems will limit its use in effluent streams.

D. LABORATORY POWDER SIZING TECHNIQUES

A number of semi-automatic techniques exist for the sizing of powder particles in the laboratory. Most of these techniques require the dispersion of the particles in a suitable liquid. The size analysis is then performed on the liquid-suspended particles.

Several of these techniques could conceivably be automated for sizing particles in effluent streams. A representative sample would first have to be collected from the effluent stream, dispersed accurately into the suitable liquid, and then sized automatically by the sizing apparatus. At least two major problems present themselves: (1) the mechanical complexity of a completely automated particle size monitoring system, and (2) the difficulty in defining the relationship between the particles as they exist in the stack and as they exist in the dispersion liquid. The first is primarily a mechanical design problem, but the second is a more basic problem.

Several configurations are suggested here as possible solutions to the problem of automating such a system. The system would consist of two major components: (1) the particle size analyzer, and (2) the equipment needed to collect a representative sample and bring it to the particle size analyzer suspended in a suitable liquid.

Several semi-automatic particle size analyzers are commercially available for sizing 0.5 - 100 μm particles suspended in a liquid. Two such instruments are the Micromeritics particle size analyzer* and the Coulter counter**. These are two of the most automated laboratory powder sizing instruments available.

The Micromeritics instrument classifies particles by size using the principle of particle sedimentation through the liquid. The particle concentration is sensed by an x-ray beam. A computerized readout system allows the adjustment of particle density, liquid density, and viscosity. The result is plotted by an X-Y plotter in terms of the "% by mass less than size" versus "equivalent particle diameter". The particles must be introduced into the instrument in the form of a liquid suspension.

The Coulter counter feeds the particles single-file through a small orifice and measures a change in the electrical conductance across the orifice as each particle passes through. The amplitudes of the resulting electrical pulses, one for each particle, are proportional to the size (volume) of the particles. The results, after appropriate classification of the electrical pulses, can be presented in several forms, such as "% by number less than size" or "number counted per size range" versus "equivalent particle diameter". As in the Micromeritics instrument, the particles must be introduced into the Coulter counter in the form of a liquid suspension. The Coulter counter liquid must be an electrolyte.

*Manufactured by: Micromeritics Instrument Corporation, 800 Goshen Springs Road, Norcross, Ga. 30071.

**Manufactured by: Coulter Electronics Industrial Division, 590 West 20th St., Hialeah, Florida 33010.

Each of the size analyzers has its own set of problems. These have been quite well described in the literature and will not be discussed here. Some of these problems may be limiting factors in the design of a fully-automated system.

However, a major problem faced by all sizing systems of this type is the design of the second component mentioned above: the equipment needed to collect a representative sample of particles from the effluent stream and bring the sample to the size analyzer suspended in a suitable liquid. No automated system of this type is known and all known design concepts appear to lack the capability of reliable, long-term, unattended operation. The two most feasible air-to-liquid particle samplers are the LEAP and MSI samplers*. The LEAP sampler uses electrostatic precipitation to collect particles from 300 to 15,000 liters per minute of air onto a film of liquid. The liquid flows continuously over the collection surface and then into a collection bottle. The MSI sampler is nearly identical except that it uses impaction rather than electrostatic precipitation and it operates at only one flow rate, 1000 liters per minute, as commercially designed. Conceptually, one of these samplers could continuously collect particles from the effluent stream and feed the resulting liquid suspension to the particle size analyzer.

Even if the design problems could be satisfactorily solved, the problem of relating the measured particle size in the liquid suspension to the particle size in the effluent stream remains. Generally, one wants to measure the size of an agglomerate just as it exists in the effluent stream. However, the agglomerate may break up or grow in the liquid suspension. The control of the agglomeration or deagglomeration process would be difficult. Also, any soluble particles would be dissolved by the liquid, and liquid or partially-liquid particles would be grossly changed in the liquid suspension. In instruments which use an electrolytic suspension, the acidity of the stack gas could change the electrolytic properties. Thus, the interpretation of data from this type of sizing system would be difficult.

For these reasons, this technique of sizing effluent particles should be approached with extreme caution.

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*Manufactured by Environmental Research Corporation, 3725 North Dunlap Street, St. Paul, Minnesota 55112.

E. A DIFFERENT SIZING CONCEPT: PARAMETRIC MEASUREMENT

The measurement of a single particle concentration parameter has rather severe limitations for characterizing an aerosol such as combustion effluent. For example, the number concentration is usually dominated by the great numbers of small particles below 0.1 μm diameter. The addition of enough 25 μm particles to double the mass concentration will cause an undetectibly small change in the number concentration. On the other hand, the mass concentration is usually dominated by the great mass of large particles primarily above 1 μm diameter. Doubling the number of 0.01 - 0.1 μm particles causes an undetectibly small change in the mass concentration in such cases. Thus, mass concentration measurements are sensitive to large particles while number concentration measurements are sensitive to small particles.

The parametric particle size measurement method would use the inherent size limitations of particle concentration sensing techniques to measure a form of particle size distribution. Several concentration sensors would be used, each sensing a different particulate parameter. For example, number, surface, and mass concentration are three potential parameters. Number concentration would be highly sensitive to small particles, surface concentration to medium-sized particles, and mass concentration to large particles. Although this method would not offer enough detailed information for many scientific research studies, it would appear to offer very useful measurements for source monitoring applications.

Particle number concentration can be measured by a condensation nuclei counter or by an electrostatic technique. Particle surface area, or a parameter similar to surface area, is measured by well-designed optical transmissometers and photometers. Particle mass is measured by beta radiation attenuation instruments. All of these techniques are discussed in detail in Volumes I and II of this report. Nearly all have been used in other applications, and adaptation of at least one sensor in each group to effluent measurements appears easily possible. Electrostatic sensors, optical transmissometers, and beta radiation attenuation have all been used on large combustion effluent stacks in the past. Thus, the design of equipment to make all three measurements simultaneously, on a continuous, monitoring basis, does not appear to be an obstacle. Further development of these techniques would not be prohibitively expensive and could probably result in reliable instruments in about 2 years.

Even though this approach would result in the measurement of only three particle concentration parameters, not in the measurement of size distributions, much information about the particle size distribution would be available from the three measurements. The number concentration measurement would be sensitive to fluctuations in the concentration of small particles. The mass concentration measurement would be sensitive to fluctuations in the concentration of large particles. The surface area measurement would be sensitive to particles in the middle size range. Thus, an increase in the emissions of large particles would be detected by a corresponding increase in measured mass concentration and

little change in the measured number concentration. The surface-area measurement would resolve whether the particles were very large (perhaps 20 μm) or close to 1 μm. An increase in the emissions of small particles would be detected by a corresponding increase in the measured number concentration, but with little change in measured mass concentration. Again, the surface area measurement would resolve whether the additional particles were very small (approximately 0.01 μm) or in the 0.1 μm range.

There are a number of other factors making this approach to particle size monitoring of source effluents attractive. Both the large and the small particles are important to air pollution. The particles above 10 μm settle onto nearby surfaces, contaminating buildings, automobiles, streets, agricultural crops, trees, rivers, lakes, etc., with possible damage due to corrosive effects. Particles below 0.1 μm remain suspended for long periods of time, contributing to global pollution, to rain nuclei, to condensation processes, to particulate-gaseous chemical interaction including photochemical smog formation, etc. These small particles grow, by condensation of vapors and by collision and agglomeration with other particles, into the intermediate size range between 0.1 and 10 μm. Particles of the intermediate size range penetrate most deeply into the human respiratory system, penetrate filters more easily than other sizes, remain airborne for long periods of time, are most visible, cause degradation of visibility, etc.

Thus, each size range is important for different reasons, and the measurement of a single particle parameter does not characterize the entire range of particles found in combustion sources sufficiently enough to relate source emissions to air pollution effects.

Theoretically, if any form of the particle size distribution can be measured with enough accuracy, any other form of the size distribution can be calculated from it. However, the resolution limitations of practical instrumentation do not allow accurate mathematical transformations to be made on aerosols such as combustion effluents. For example, any measurement of particle mass concentration within various size ranges will ignore the insignificant mass of the large numbers of 0.01 - 0.1 μm particles. Any measurement of particle number concentration within various size range will ignore the insignificant numbers of larger particles above 10 μm. Instrument accuracies to 8 or 10 significant digits of concentration and over 8 or 10 orders of magnitude of concentration would be necessary to avoid this problem. Thus, measurement of the entire range with a single instrument is not possible at this time and does not appear probable. Measurement of a single parameter over the entire range with several instruments is also not possible.

The mass concentration and the mass size distribution are nearly useless to the meteorologist studying global pollution patterns and rain formation, to the city air pollution official concerned with predicting the rate of photochemical smog formation, and to the researcher studying the dynamics of pollution in the submicron size range. These applications require a measurement which is sensitive to the particles of primary interest, i.e., the submicron particles. The number concentration and number size distribution are two such measurements.

The number concentration and number size distribution are nearly as useless to the pollution control official concerned with dust fall on various surfaces and the stack owner concerned with complying with pollution control regulations written in terms of particulate mass. These persons require the mass concentration and mass size distribution; parameters which are of primary interest to them.

Likewise, the pollution control official concerned with reducing the visible smoke from stacks and the visible haze over a city, and the people concerned with reducing the harmful health effects of particulate pollution will be most concerned with the particles in the middle size range: from 0.1 to 10 μm. Optical measurements and particle surface area sensors are usually most sensitive to particles in this size range.

This does not mean, however, that three separate and complete size distributions would have to be measured to satisfy all applications. Rather, it appears that sufficient data may be provided by three single concentration measurements of these particle properties: (1) number concentration, (2) surface or cross-sectional area concentration, and (3) volume or mass concentration. This would satisfy most of the requirements for monitoring applications.

Measurements of other effluent particulate parameters may also prove useful. For example, the mass of particles within the respirable range as defined by the American Conference of Governmental Industrial Hygienists[133] may be a useful measure of the harmfulness of effluent particles from a health effects viewpoint. The respirable mass concentration is essentially the portion of the total mass concentration which remains airborne for long periods of time. The difference between total mass concentration and respirable mass concentration is essentially the fraction of particulate emissions which settles to the ground near the effluent source. Thus, measurement of respirable mass concentration and total mass concentration provides another interesting combination for continuous monitoring applications.

Some of the parameters which may be of interest for particle size monitoring of source effluents are:

Number concentration
Surface concentration
Volume or mass concentration
Visible or visibility measurement
Respirable
Suspended
Settleable
Rain and snow nuclei
Potential photochemical smog aerosol formation.

Theoretically, the result of this parametric approach appears to be practical methods to measure not only the concentration of particulate emissions in terms useful to a wide range of pollution control personnel, but also much of the necessary particle size information. The necessary hardware is either already developed or can be developed within about two years. The equipment will not be prohibitively expensive, even for use as a continuous monitor on every large combustion emissions source.

The authors recommend an intensive investigation into the potential usefulness of this approach. The response to each measurement in the system to reasonable, expected effluent changes should first be studied. This would isolate conceptual problems and define additional benefits of such measurements. The conceptual evaluation should be followed or accompanied by development of the appropriate concentration monitoring instruments capable of operating in a total system. The development of concentration sensing instruments for this application requires no development in addition to the concentration sensors needed for the monitoring of single concentration parameters. Thus, particle size information sufficient for most monitoring applications can be obtained with little additional development of equipment.

F. SUMMARY AND CONCLUSIONS

1. Particle size distribution is one of the three most important parameters in defining the relative potential harmfulness of particulate emissions. A single particle concentration measurement cannot define the relative potential harmfulness of an effluent stream without information about the relative concentration within several size ranges. Particle size measurements are urgently needed for research applications, for control equipment evaluation, and for air pollution control monitoring.

2. Most size distribution measurements of combustion effluent particles made in the past used available equipment which severely limited the size range effectively sampled. The technique used for most such measurements could not measure particles below 2 μm or over 100 μm leading to the conclusion that nearly all effluent particles are within the 2 - 100 μm size range.

3. Demonstrated size distribution measurements of combustion effluent particles in the micron and submicron range are almost nonexistent. This size range appears to be the most important for most air pollution considerations.

4. There is no single preferred way of presenting particle size distribution data which is useful for every application. The preferred size measurement technique is usually the method which most directly obtains the desired information in its final form. An important consideration is whether particle number, surface area, volume, mass, or some other parameter is needed for any given application.

5. No sizing instrument can classify particles over the entire particle size range of interest (from 0.001 to over 100 μm). The alternative is to combine several techniques to cover the entire range or to choose the range of primary interest and find an appropriate technique for that range. Both of these approaches require very careful interpretation of the data.

6. Aerodynamic particle size is the most useful size parameter in most applications.

7. Table B.5 lists the operable size ranges of various combinations of size classifiers and concentration sensors. The recommendations for particle size measurements of most combustion effluents for most air pollution applications are outlined below:

   a. An impaction size classifier (an aerodynamic classsifier) coupled with a beta radiation attenuation, piezoelectric quartz crystal, or photometric concentration sensor appears to be most applicable

to detailed effluent stream particle size measurements at this time. The impactor cannot classify particles less than about 0.2 or greater than about 30 μm. However, this appears to be the range of primary interest for many, perhaps most, applications. The particles below the last impactor cutoff can be lumped into one size range and, with appropriate attention given to correct design of the sampling system particles larger than the first cutoff can be lumped into another size range. Thus, although all size range cutoffs are between about 0.2 and 30 μm, the entire range of size passing through the device is accounted for. At the present, this approach appears to offer the most promose of success as a single automated particle sizing tool in effluent streams.

b. If size classification below 0.2 μm is necessary, electrostatic techniques (0.005 - 0.6 μm) or Brownian diffusion techniques (0.001 - 0.05 μm) must be used. Although not yet applied to stack effluents, an electrostatic technique has demonstrated high resolution in the 0.01 - 0.2 μm range on laboratory, atmospheric, and small, flame-generated aerosols. The Brownian diffusion technique, used only for specialized laboratory measurements to date, is the only known method for sizing 0.001 - 0.005 μm particles. Further research and development of both of these techniques is necessary before automated instruments for stacks could result. No other method of classifying particles by size significantly below 0.2 μm is known.

c. The cyclone classifier can aerodynamically separate an effluent aerosol sample into two size fractions. The size split must be between about 0.5 μm and 20 μm and is not very sharp. The cyclone classifier has been used extensively for separating the "respirable fraction" from industrial hygiene aerosols and may prove useful for similar application in effluent streams.

8. Although optical particle counters are severely limited for effluent stream measurements with their present design, major modification may significantly reduce the problems. The lower size limit of optical particle counters is about 0.2 μm. The upper limit, determined by the sampling system, is about 30 μm; and may be improved by development of an instrument which can operate directly within the effluent stream. Another problem at present is the high dilution with clean air required to prevent coincidence.

9. Holography offers some promise for research sizing applications in effluent streams. However, routine use appears limited by the cost and complexity of the equipment. In effluent streams, its ability to obtain a 3-dimensional record (photograph) of the effluent particles

without disturbing the flow is highly attractive. However, present holography is limited by the smallest particle which can be individually resolved (a few microns) while still maintaining a practical depth-of-field (perhaps greater than a centimeter) and distance-from-apparatus-to-particle (greater than 3 meters for use in effluent streams). Holography is developing rapidly and may prove more useful in the future as the equipment cost and complexity decreases, and as resolution increases.

10. Powder and slurry particle sizing techniques do not appear applicable to effluent streams because of the difficulty in relating the particle size measurement (made in a liquid) to the actual airborne particle.

11. A different technique, which appears to offer a practical method for long-term, continuous monitoring in effluent streams uses the size limitations of several different concentration sensors to effectively measure particle concentration within several size ranges. The technique would use (1) a beta radiation attenuation sensor to measure the total particulate mass concentration (sensitive to D_p^3, or large particles in the 1 - 100 μm range), (2) a transmissometer to measure opacity (roughly sensitive to D_p^2, or particles primarily from 0.1 - 10 μm) and (3) a condensation nuclei counter or electrostatic counter to measure the particle number concentration (sensitive to the number of particles, or to particles from 0.001 - 1.0 μm). Analysis of the 3 simultaneous measurements would appear to offer sufficient particle size information for most continuous air pollution monitoring applications. Measurement of total mass concentration and respirable mass concentration offers another interesting combination of particulate parameters. Nearly all hardware needed for these measurements already exists. Further investigation and testing of this approach is recommended.

12. Although this report addresses itself to the heart of particle sizing apparatus (the size classifier and concentration sensor), the equally important problem of particle sampling must also be considered. The problem of delivery of truly representative samples of effluent to the measuring instrument has not yet been solved. Although one can tolerate some agglomeration of fragmentation of particles in a sampling system for total concentration measurement, such changes in particle size cannot be permitted in a particle sizing system. Questions related to the conditioning of the effluent (dilution, heating, cooling, etc.) prior to measurement by most sizing instruments must also be investigated thoroughly. Emphasis must be placed on a thorough investigation of the particle size changes which take place in effluent sampling systems. This area merits at least as much attention as the particle sizing instrument itself. The advantages offered by any potential sizing instrument which does not require removal of a sample from the stack must be emphasized. Unfortunately, all of the practical, available techniques require sample extraction.

G. REFERENCES

27 Peterson, C. M., and Paulus, H. J., "Continuous Monitoring of Aerosols Over the 0.001- to 10-micron Spectrum", American Industrial Hygiene Association Journal, p. 111-122 (Mar - Apr 1968).

29 Lundgren, D. A., "An Aerosol Sampler for Determination of Particle Concentration as a Function of Size and Time", APCA Journal, V. 17, no. 4, p. 225-229 (Apr 1967).

40 Liu, B.Y.H., Marple, V. A., and Yazdani, H., "Comparative Size Measurements of Monodisperse Liquid Aerosols by Electrical and Optical Methods", Environmental Science and Technology, V. 3, no. 4, p. 381-386 (Apr 1969).

42 Clark, W. E., and Whitby, K. T., "Concentration and Size Distribution Measurements of Atmospheric Aerosols and a Test of the Theory of Self-Preserving Size Distributions", Journal of Atmospheric Sciences, V. 24, no. 6, p. 677-687 (Nov 1967).

56 Liu, B.Y.H., Whitby, K. T., and Yu, H.H.S., "On the Theory of Charging of Aerosol Particles by Unipolar Ions in the Absence of an Applied Electric Field", Journal of Colloid & Interface Science, V. 23, p. 367-387 (1967).

61 Whitby, K. T., and Peterson, C. M., "Electrical Neutralization and Particle Size Measurement of Dye Aerosols", Industrial & Engineering Chemistry Fundamentals, V. 4, no. 1, p. 66-72 (Feb. 1965).

68 Whitby, K. T., and Clark, W. E., "Electric Aerosol Particle Counting and Size Distribution Measuring System for the 0.015 to 1 μ Size Range", Tellus, V. 18, p. 573-586 (1966).

70 Kerker, M., Farone, W. A., Smith, L. B., and Matijevic, E., "Determination of Particle Size by the Minima and Maxima in the Angular Dependence of the Scattered Light, Range of Validity of the Method", Journal of Colloid Science, V. 19, p. 193-200 (Mar 1964).

120 Thomas, A. L., Jr., Bird, A. N., Jr., Collins, R. H.,III, and Rice, P.C., "A Portable Photometer and Particle Size Analyzer", ISA Journal, V. 8, p. 52-56 (Jul 1961).

123 Goetz, A., and Preining, O., "The Aerosol Spectrometer and Its Application to Nuclear Condensation Studies", Monograph No. 5., Geophysical Union. (1960).

124 Thompson, J. K., "Determination of Aerosol Size Distribution by Jet Impactor-Light Scattering Technique", Analytical Chemistry, V. 29, p. 1847-50 (1957).

143 Hodkinson, J. R., and Greenfield, J. R., "Response Calculations for Light-Scattering Aerosol Counters and Photometers", Applied Optics, V. 4, p. 1463-1474 (1965).

154 Flesch, J. P., Norris, C. H., and Nugent, A. E., Jr., "Calibrating Particulate Air Samplers with Monodisperse Aerosols: Application to the Andersen Cascade Impactor", American Industrial Hygiene Assoc. Journal, V. 28, no. 6, p. 507-516 (Nov - Dec 1967).

208 Crandall, W. A., "Development of Standards for Determining Properties of Fine Particulate Matter", ASME - Paper 64-WA/PTC-3, for meeting Nov. 29 - Dec. 4, 9 p. (1964).

239 Anon., Determining the Properties of Fine Particulate Matter, American Society of Mechanical Engineers, PTC-28-1965, 40 p. (1965).

252 Rogallo, V. L., and Neuman, F., "A Wide-Range Piezoelectric Momentum Transducer for Measuring Micrometeoroid Impacts", Ames Reseach Center, Moffett Field, Calif., Clearinghouse No. NASA TN D-2938 (Jul 1965).

274 Anon., "Dust Emission Control in Calcium Carbide Production", Translated from German, Clearinghouse No. TT 68 50469/2 (Dec 1965).

276 Nelson, M. B., "Fabrication of Particle Counters for Clean Rooms", IIT Research Institute, Chicago, Ill., NASA Tech. Brief 67-10076 (Jul 1966)

290 Goetz, A., and Kallai, T., "Determination of Size and Mass Distribution of Aerosols", Symposium on Air-Pollution Measurement Methods, Special Tech. Pub. No. 325, ASTM, p. 40-55 (1964).

294 Mitchell, R. I., and Pilcher, J. M., "Cascade Impactor for Measuring Aerosol Particle Size", Industrial and Engineering Chemistry, V. 51, p. 1039-1042 (1959).

354 Goetz, A., and Kallai, T., "Instrumentation for Determining Size- and Mass-Distribution of Submicron Aerosols", APCA Journal, V. 12, no. 10, p. 479-486 (Oct 1962).

369 Goetz, A., "Methods for Measuring Particle Composition in Photo-activated Aerosols" APCA Journal, V. 14, no. 6, p. 213-219 (Jun 1964).

370 Zinky, W. R., "A New Tool for Air Pollution Control, the Aerosol Particle Counter", APCA Journal, V. 12, no. 12, p. 578-583 (Dec 1962).

505 Goetz, A., "An Instrument for the Quantitative Separation and Size-Classification of Air-Borne Particulate Matter Down to 0.2 Micron", Geopfis, Pura. Appl., V. 36, p. 49-69 (1957).

546 Goetz, A., "The Aerosol Spectrometer - A New Instrument for the Analysis of Air-Borne Particles in the Submicron Range", Public Works, V. 90, no. 2, p. 91-93 (Feb 1959).

578 Martens, A. E., "Errors in Measurement and Counting of Particles Using Light Scattering, APCA Journal, V. 18, 661-663 (Oct 1968).

580 Ogle, H. M., "Particle Counting Techniques Available for Aerosol Research", APCA Journal, V. 10, p. 657-659 (Oct 1968).

598 Mumma, V. K., Thomas, A. L., Jr., and Collins, R. H., III., "A Particle Size Analyzer for Aerosols", Army Biological Labs., Frederick, Md., Clearinghouse No. AD 636 858 (1962).

615 Sinclair, D., "A New Photometer for Aerosol Particle Size Analysis", APCA Journal, V. 17, no. 2, p. 105-108 (1967).

638 Rumpf, H., "The Particle Size Analysis of Industrial Dusts", Staub-Reinhalt der Luft, (Engl. Trans.), V. 25, no. 1, p. 17-26 (Jan 1965).

649 Stober, W., "Measuring Methods to Describe the Physical Properties of Aerosol Systems", Staub-Reinhalt der Luft (Engl. Trans.), V. 25, no. 9, p. 34-41 (Sep 1965).

670 Martens, A. E., and Fuss, K. H., "An Optical Counter for Dust Particles", Staub-Reinhalt der Luft, (Engl. Trans.), V. 28, no. 6, p. 14-18 (Jun 1968).

675 Simecek, J., and Kubalek, J., "Experience with Cyclone Preseparation in Dust Sampling", Staub-Reinhalt der Luft (Engl. Trans.), V. 28, no. 10, p. 24-31 (Oct. 1968).

680 Whitby, K. T., and Liu, B.Y.H., "Generation of Countable Pulses by High Concentrations of Subcountable Sized Particles in the Sensing Volume of Optical Counters", Journal of Colloid & Interface Science, V. 25, no. 4, p. 537-546 (1967).

685 Parker, G. W., and Buchholz, H., "Size Classification of Submicron Particles by a Low-Pressure Cascade Impactor", Oak Ridge, Tenn., Clearinghouse No. ORNL-4226 (Jun 1968).

756 Martens, A. E., and Keller, J. D., "An Instrument for Sizing and Counting Airborne Particles", American Industrial Hygiene Assoc. Journal, V. 29, p. 257-267 (May - Jun 1968).

818 Brown, P. M., and Hochrainer, D., "Conical Aerosol Spectrometer, Cylindrical Aerosol Spectrometer", National Center for Atmospheric Research, Boulder Colorado, Clearinghouse No. PB 180 880.

824 Neitzel, W. E., "A High-Volume, Real-Time Aerosol Monitor", Sandia Lab., Albuquerque, N. M., Clearinghouse No. SC-DR-69-56 (Jun 1969).

833 Heywood, H., "Fundamental Principles of Sub-Sieve Particle-Size Measurement", paper presented at Inst. of Mining & Metallurgy Symp. on Mineral Dressing, London, Eng., Paper No. 6 (Sep 23-25, 1952).

834 Higgins, R. I., and Dewell, P., "The Measurement of Airborne Dust Concentration in Iron-Foundries Using the Hexlet Dust Sampler, B.C.I.R.A. Journal, V. 8, no. 3, p. 425-436 (May 1960).

842 Kratohvil, J. P., and Smart, C., "Calibration of Light-Scattering Instruments, III. Absolute Angular Intensity Measurements on Mie Scatterers", Journal of Colloid Science, V. 20, no. 8, p. 875-892 (1965).

912 Walton, W. H., "Theory of Size Classification of Airborne Dust Clouds by Elutriation", British Journal of Applied Physics, Supp. no. 3, p. S29-S39 (1954).

925 Stober, W., and Flachsbart, H., "Size-Separating Precipitation of Aerosols in a Spinning Spiral Duct", Environmental Science & Technology, V. 3, no. 12, p. 1280-1296 (Dec 1969).

948 Mercer, T. T., "The Stage Constants of Cascade Impactors", Lovelace Foundation, Albuquerque, N.M., Clearinghouse No. LF-12 (Oct 1963).

949 Whitfield, W. J., and Mashburn, J. C., "Development of an Increased Sampling Rate Monitoring System", Sandia Lab., Albuquerque, N. M., Clearinghouse No. SC-RR-66-585 (Oct 1966).

957 Brink, J. A., Jr., "Cascade Impactor for Adiabatic Measurement", Industrial & Eng. Chemistry, V. 50, no. 4, p. 645-648 (Apr 1958).

995 Mercer, T. T., "The Interpretation of Cascade Impactor Data", American Industrial Hygiene Assoc. Journal, V. 26, p. 236-241 (May - Jun 1965).

996 Hounam, R. F., and Sherwood, R. J., "The Cascade Centripeter: A Device for Determining the Concentration and Size Distribution of Aerosols", American Industrial Hygiene Assoc. Journal, V. 26, p. 122-131 (Mar - Apr 1965).

1002 Lippmann, M., "Review of Cascade Impactors for Particle Size Analysis and a New Calibration for the Casella Cascade Impactor", American Industrial Hygiene Assoc. Journal, V. 20, p. 406-416 (Oct 1959).

1052 Ettinger, H. J., "Survey of Technique Employed to Define Aerosol Respirable Dust Concentration and Particle Size Characteristics", University of California, Los Alamos, N. M., Clearinghouse No. LA-4249.

1066 Kiktenko, V. S., Safronov, Y. P., Kudryautsev, S. I., Fedorov, B. F., Pushcin, N. I., and Fedorovich, A. A., "Photoelectric Count of the Number of Aerosol Particles of Organic and Inorganic Origin", Engl. Trans. from: Gifiyenai Sanitariary, Moscow, V. 26, no. 2, p. 47-53, Feb. 1961, Clearinghouse No. JPRS-8334 (May 1961).

1069 Ramanujam, M., and Venkateswarlus, D., "Particle-Size Analysis" Chemical Age of India, V. 19, no. 11, p. 975-983 (1968).

1119 Stober, W., "Design and Performance of a Size-Separating Aerosol Centrifuge Facilitating Particle-Size Spectrometry in the Submicron Range", Assessment Airborne Radioactivity, Proc. Symp., Vienna, p. 393-404 (1967).

1120 Raabe, O. G., "Calibration and Use of the Goetz Aerosol Spectrometer", Assessment of Airborne Radioactivity, Proc. Symp., Vienna, p. 417-431 (1967).

1128 Moroz, W. J., Withstandley, V. D., and Anderson, G. W., "A Portable Counter and Size Analyzer for Airborne Dust", Review of Scientific Instruments, V. 41, no. 7, p. 978-983 (Jul 1970).

1201 Van de Hulst, H. C., Light Scattering by Small Particles, Wiley (1957).

1210 Randall, L. M., and Keller, J. D., "Electro-Optical Aerosol Counter Inst., AIHA Conf., Houston, Texas (1955).

1211 Davies, C. N., ed. Aerosol Science, Academic Press (1966).

1215 Kerker, M., The Scattering of Light and Other Electromagnetic Radiation, Academic Press (1969).

1216 Green, H. L., and Lane, W. R., Particulate Clouds: Dusts, Smokes and Mists., E. and F. N. Spon Ltd., London (1964).

1223 Chuan, R. L., "An Instrument for the Direct Measurement of Particulate Mass", Aerosol Science, V. 1, p. 111-114 (1970).

1257 Matthews, B. J., and Kemp, R. F., "Investigation of Scattered Light Holography of Aerosols and Data Reduction Techniques", TRW Systems Group, Redondo Beach, Calif., TRW Report No. 14103-6002-RO-00 under NAPCA Contract CPA 70-4 (Nov 1970).

1273 Israel, G. W., "Investigations of Aerosol Beams", Staub-Reinhalt der Luft, (Engl. Trans.), V. 29, no. 5, p. 5-8 (May 1969).

1276 Whitby, K. T., and Liu, B.Y.H., "Atmospheric Particulate Data - What Does It Tell Us About Air Pollution?", Paper Presented at 11th Conference Methods in Air Pollution and Industrial Hygiene Studies, Berkeley, Calif., Mar. 30, 31, and Apr 1, 1970.

1279 Matthews, B. J., and Kemp, R. F., "Holographic Determination of Injected Limestone Distribution in Unit 10 of the Shawnee Power Plant", TRW Systems Group, Redondo Beach Calif., TRW Report No. 14103-6001-RO-00 under NAPCA Contract CPA 70-4 (Jun 1970).

1285 Paulus, H. J., and Peterson, C. M., "Urban Aerosols: Count Size Related to Meteorological Data", School of Public Health, University of Minnesota, Minneapolis, Minnesota, Final Report (Nov 1969).

1299 Knight, G., "A Simple Method for Determining Size Distribution of Airborne Dust by Its Settling Velocity", paper presented at the American Industrial Hygiene Association Annual General Meeting, Detroit, Mich., May 19, 1970.

1331 Todd, W. F., Hagan, J. E., and Spaite, P. W., "Test Dust Preparation and Evaluation", Public Health Service, U. S. Department of Health, Education, and Welfare, Cincinnati, Ohio.

1332 Graham, A. L., and Hanna, T. H., "The Micro-Particle Classifier", Ceramic Age, (Sep 1962).

1333 Fuchs, N. A., The Mechanics of Aerosols, Published by the MacMillian Company, New York, N.Y. (1964).

1334 Anon., "Threshold Limit Values of Airborne Contaminants for 1968", American Conference of Governmental Industrial Hygienists (1968).

1335 Lippmann, M., and Harris, W. B., "Size-Selective Samplers for Estimating Respirable Dust Concentrations", Health Phys., 8:155-163 (1962).

1340 Marple, V. A., "A Fundamental Study of Inertial Impactors", Ph. D., Thesis, Dept. of Mechanical Engineering, University of Minnesota (Sep 1970).

1341 Dyment, J., "Use of a Goetz Aerosol Spectrometer for Measuring the Penetration of Aerosols Through Filters as a Function of Particle Size", Aerosol Science, V. 1, p. 53-67 (1970).

1342 Khmelevtsov, S. S., "A Size-Separation Collector for Sampling Aerosols From Curvilinear Flow", Dept. of the Army, Fort Detrick, Frederick, Maryland, Clearinghouse No. AD 678 123 (Nov 1967).

1343 Redkin, J. N., "Properties of Atmospheric Aerosol Measured with a Centrifugal Spectrometer", Journal of Geophysical Research, V. 75, no. 18, (Jun 1970).

1344 Whitby, K. T., Husar, R., McFarland, A. R., and Tomaides, M., "Generation and Decay of Small Ions", University of Minnesota, Minneapolis, Minnesota., Prepared for National Air Pollution Control Admin., under USPHS Research Grant No. AP 00136-08 (Jul 1969).

1354 Lippmann, M., and Kydonieus, A., "A Multi-Stage Aerosol Sampler for Extended Sampling Intervals", American Industrial Hygiene Association Journal, p. 730-737 (Nov - Dec 1970).

1357 Herdan, G., Small Particle Statistics, 2nd ed., Academic Press Inc., New York, N.Y. (1960).

1361 Israel, G. W., and Whang, J. W., "Characteristics of Aerosol Beams", paper presented at Second International Clean Air Congress, Washington, D. C., Dec 6 - 11, 1970.

1362 Dahneke, B. E., and Friedlander, S. K., "Velocity Characteristics of Beams of Spherical Polystyrene Particles", Aerosol Science, V. 1, p. 325-339 (1970).

1363 May, K. R., "The Cascade Impactor: An Instrument for Sampling Coarse Aerosols", Journal of Scientific Instrumentation, V. 22, p. 187 (1945).

1364 Wells, B. J., "An Evaluation of the May Type of Cascade Impactor", Health Physics, V. 13, p. 1001 (1967).

1365 Sonkin, L. S., "A Modified Cascade Impactor", Journal of Industrial Hygiene and Tox., V. 28, p. 269 (1946).

1366 Laskin, S., In C. Voegtilin and H. C. Hodge, eds. Pharmacology and Toxicology of Uranium Compounds, V. 1, p. 463-505, McGraw-Hill, New York (1949).

1367 Wilcox, J. D., "Design of a New Five-Stage Cascade Impactor", A.M.A. Arch. Ind. Hyg. & Occup. Med., V. 7, p. 376 (1953).

1368 Ranz, W. E., and Wong, J. B., "Impaction of Dust and Smoke Particles", I & E Chem., V. 44, p. 1371 (1952).

1369 Ranz, W. E., and Wong, J. B., "Jet Impactors for Determining the Particle-Size Distribution of Aerosols", A.M.A., Arch. Ind. Hyg. Occup. Med., V. 5, p. 464 (1952).

1370 Stern, S. C., Zeller, H. W., and Schekman, A. I., "Collection Efficiency of Jet Impactors at Reduced Pressures", I & EC Fundamentals, V. 1, p. 273 (1962).

1371 Davies, C. N., Aylward, M., and Leacey, D., "Impingement of Dust from Air Jets", A.M.A. Arch. Ind. Hyg. Occup. Med., V. 4, p. 354 (1951).

1372 Mercer, T. T., and Chow, H.Y., "Impaction from Rectangular Jets", Journal of Coll. and Interface Science, V. 27, p. 75 (1968).

1373 Pilcher, J. M., Mitchell, R. I., and Thomas, R. E., "The Cascade Impactor and Particle-Size Analysis of Aerosols", Proc. of 42nd Annual Meeting of Chemical Specialties Manufacturers Association, Inc., Dec. 6-7, 1955.

1374 McFarland, A. R., and Zeller, H. W., "Study of a Large-Volume Impactor for High-Altitude Aerosol Collection", General Mills, Inc., Electronics Division, Report No. 2391, Contract AT(11-1)-401 (1963).

1375 Zeller, H., "Large Volume Impactor Collector", Applied Science Division, Litton Systems, Inc., St. Paul, Minn., Report No. 2893, Project No. 89125 (1965).

1376 Andersen, A. A., "New Sampler for the Collection, Sizing, and Enumeration of Viable Airborne Particles", Journal of Bact., V. 76, p. 471 (1958).

1377 Andersen, A. A., "A Sampler for Respiratory Health Hazard Assessment", American Industrial Hygiene Association Journal, V. 27, p. 160 (1966).

1378 Mercer, T. T., and Stafford, R. G., "Impaction from Round Jets", Ann. Occup. Hyg., V. 12, p. 41 (1969).

1379 McFarland, A. R., and Husar, R. B., "Development of a Multistage Inertial Impactor", University of Minnesota Particle Technology Laboratory Publication 120 (1967).

1380 Mercer, T. T., Tillery, M. I., and Newton, G. J., "A Multistage, Low Flow Rate Cascade Impactor", Aerosol Science, V. 1, p. 9 (1970).

1383 Hounam, R. F., "The Cascade Centripeter", United Kingdom Atomic Energy Authority Research Group, Harwell, Berkshire, England (1964).

1390 Husar, R. B., "Coagulation of Knudsen Aerosols", Ph.D. Thesis, University of Minnesota, March 1971.